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bladed barite (white) mag. 580×; ppl	botryoidal barite mag. 538×; xpl	spherulitic barite mag. 584×; xpl
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The Geoff Brown Memorial Lecture: Making and Breaking Mountains

Tom Argles, Department of Earth Sciences, The Open University

Introduction

Thank you, Joe [Jennings, OUGS Chairman — Ed.], for that kind introduction; I am very pleased to be invited here today. And since this is the Geoff Brown Memorial lecture, I thought that I would start with a picture of a volcano [slide shown — Ed.] — this is in fact Mount Unzen in Japan, which was the site of an eruption in the early 1990s, including famous footage of a pyroclastic flow. I should also apologise before I start, to those of you who are much better vulcanologists than myself, for my general ignorance of vulcanology, as I have rather rashly decided to talk about volcanoes for a substantial part of this talk.

As is traditional, I would like to thank the many colleagues listed here [a slide of colleagues' names was shown at this point — Ed.] who have helped me in my work, largely because if I don't, they'll come after me with guns.

What is a mountain?

So first of all, what is a mountain? Well, most of us would probably agree that Everest, the distant pyramid in the background of this slide is a mountain, as well as Cho Oyo to the right [slide of Mts Everest and Cho Oyo shown — Ed.]. But what about this thing in the middle distance here? Not so impressive. And this even smaller lump in the foreground – perhaps we would call that a hill. Well, I looked up definitions of a mountain, and came across this one: "A natural elevation of the Earth's surface having considerable mass, generally steep sides, and a height greater than that of a hill." So I looked up a definition for 'hill', and found this, startlingly similar, one: "A well-defined natural elevation smaller than a mountain." This is not entirely satisfactory! But in fact there is no formal height that defines a mountain; it is more a matter of perception. I work in the Himalayas a lot, so a hill has to be pretty impressive before I will label it a mountain. Conversely, someone from East Anglia might consider Gog and Magog to be mountains…

Now, there used to be a definition: in Britain the Ordnance Survey defined a mountain as anything 1000ft or more above sea level. This quaint notion was the subject of a book, turned into a film, about Garth mountain (or hill), in the Welsh borders. So this is for Hugh Grant (or maybe Tara Fitzgerald) fans. When the hill was first surveyed, it was classed as a hill, so the villagers carted piles of soil up to raise the summit above the required 1000ft, and a second survey proved it to be a mountain. I should point out that I still maintain the stringent standards of field attire displayed by Hugh Grant in this picture! [slide shown of Hugh Grant from the film — Ed.]

How to make a mountain

So what ingredients do you need for a mountain? The first is elevation. Can you simply pile up material on the Earth's surface to make a mountain like this one, the volcano El Misti in Peru? [slide shown — Ed.] In fact, this is what many volcanoes appear to do: they erupt impressive volumes of what I will loosely call 'stuff' and dump it in piles. Here is the recent eruption of the volcano Ruapehu, in New Zealand, dumping a load of ash onto what is actually a ski resort (Figure 1).

Figure 1 Ruapehu volcano, New Zealand.

Exactly how much 'stuff' do volcanoes erupt? This is Mt Pinatubo erupting, in June 1991, in the Philippines [slide of Mt Pinatubo shown — Ed.]. That threw out 4¼ cubic miles (sorry – I must have stolen this diagram from an American site) of material, the same as another famous eruption, Krakatau. By comparison, Mt St Helens in 1980 was pretty titchy, and Vesuvius in AD 79 was not much bigger. Tambora (1815) was rather more impressive: 19 cubic miles, and much earlier, Yellowstone (600,000 BC) threw out 300 cubic miles of 'stuff'. But even this was topped by the eruption that formed this caldera. Toba Lake in Sumatra, Indonesia is 100km long and 30km wide, and it is estimated that 670,000 cubic miles of material was ejected in this event, about 70,000 years ago. So volcanoes erupt lots of material, and can even build up above sea level. In fact, many of these volcanoes are arc volcanoes, formed above subduction zones; some of them are marked on this slide showing the 'Ring of Fire' round the Pacific Ocean [slide shown of Pacific Ocean and the locations of volcanoes around its edges — Ed.].

These are some of the most destructive volcanoes, mainly due to the high volatile content of the magmas. But there is another volcano that has built up above sea level here: Hawaii. Mauna Kea does not look much like a mountain in profile, but it rises 10.2km from its base on the ocean floor — only 4.2km of that is above sea level. There is a similarly shaped volcano that dwarfs even Mauna Kea, though — Olympus Mons on Mars, at 27km high, is about three times the height of Everest. And it is huge: here is an image I found with Olympus Mons overlain on Spain – quite an impressive mountain (Figure 2, *overleaf*)!

How are volcanoes built?

There are several ways to build a volcano. Some, like Mauna Kea, ooze lava out quite slowly and calmly — typically illustrated by *toey pahoehoe* on Hawaii [slide shown — Ed.]. More vigorous lava eruptions can build up spatter cones, as in the fire fountains on Etna, Sicily, and in pyroclastic flows. I have already mentioned ash fall; and finally, here is a picture of a smoke ring, from Bocca Nuova on Etna [slide shown — Ed.], which has nothing to do with building volcanic edifices, but I just had to show it! Ash fall, pyroclastic flows and lahars on Plymouth, the capital

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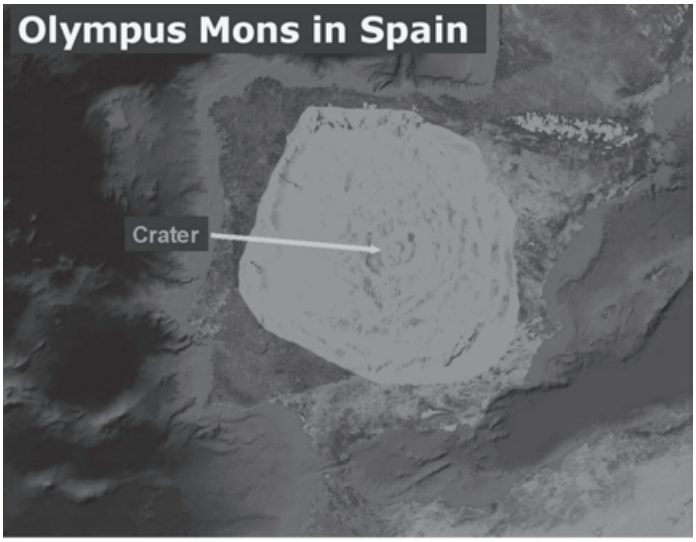

Figure 2 Plan of Mount Olympus on Mars, overlain on a map of Spain (from http://earthissquare.com/2006/02/26/so-just-how-big-is-olympus-mons/).

of Montserrat, had devastating effects [slide shown of damage to Plymouth— Ed.]. Even in a few years, the shoreline has built seaward considerably, and two-storey houses are almost submerged. After the most recent eruptions only the top of the church tower was left poking up out of the ash.

So volcanic activity is continuous, somewhere on the planet; and volcanoes do not even stop at night, as a slide of Villarica in Chile erupting at night shows. If we return to Hawaii, a single volcano can be seen as a 'point load' on the crust, which flexes under its weight. So, in cross-section, volcanoes have roots supporting them. In fact, just like an iceberg, most of a mountain's mass lies beneath sea level. But do volcanoes actually thicken crust? Some, like Hawaii or arc volcanoes, extract melt from the mantle and add this to the crust, but does this account for all the material in, say, the Andes? Certainly some of the Andean range is composed of batholiths, but these never represent more than 40% of the excess mass. Most of the thick crust beneath the Bolivian Altiplano was created by tectonic deformation; in some cases accounting for 90% of the excess mass. You can see the ridges to the east of Bolivia marking a vast fold-and-thrust belt adding to the Andes today; and basement uplifts to the south representing the same process. The hot arc crust, being weak, deforms quite easily to produce these mountains (Figure 3).

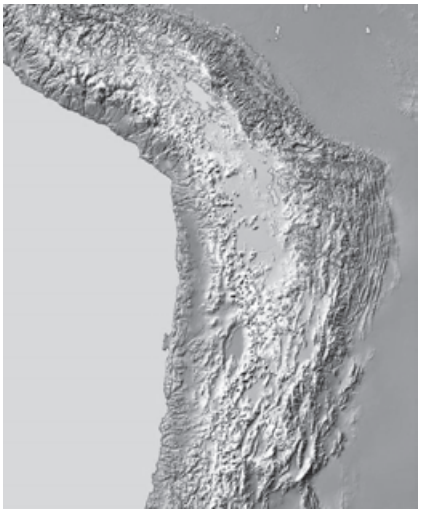

Figure 3 DEM of the Central Andes, showing the Altiplano, the sub-Andean fold and thrust belt to the east and basement uplifts in the south-east (courtesy of NASA).

Is thickened crust enough?

If we look for Earth's major mountains — the Himalayas, the Alps, the Andes, the Rockies — we can see that they coincide with regions of thick crust. How does crust thicken? Well, it can break, by faulting; or bend, on a range of scales from a metre or so, to these 100m folds in southern Tibet [slide of Tibetan folding — Ed.].

But is thickened crust alone enough to form mountains? To answer this question we can look at the Tibetan Plateau. Although underlain by crust as thick as under the Himalayas, the plateau is pretty flat — certainly not mountainous. Lake Titicaca, on the edge of the Bolivian Altiplano is another flat area on thickened crust. Another such elevated region is the Grand Canyon in Arizona, part of the Colorado Plateau — again, very flat, except for the canyon itself.

What is needed is the second ingredient for a mountain — steepness; and this is achieved, as at Bryce Canyon, Utah, by erosion. Fortunately, areas of high elevation are commonly glaciated, and glaciers are very efficient erosive agents, creating quite spectacular landscapes even in what you might call relatively modest mountains, such as in Wasdale in the English Lake District.

Mountains, rivers and climate

Mountains also tend to generate their own weather. A good example is on Nanga Parbat in Pakistan, where the surrounding region is quite arid, with precipitation of <210mm per annum, while above 4500m, precipitation rises to more than 8000mm (Figure 4).

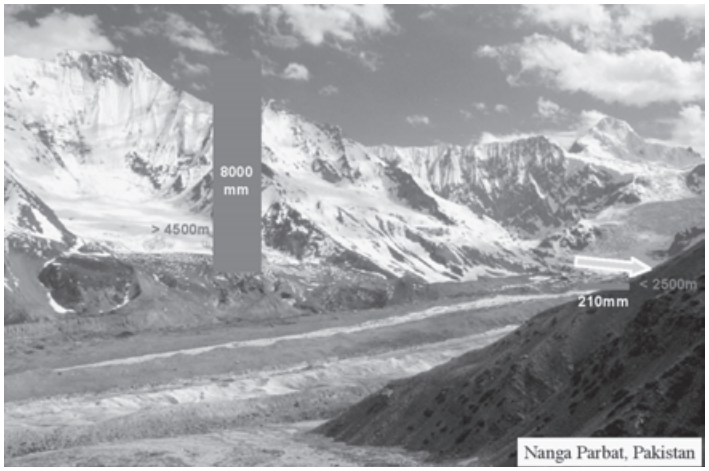

Figure 4 Nanga Parbat, Pakistan, with superimposed precipitation scales.

This pattern is repeated all along the Himalayas, because the mountains are watered by the monsoon rains, whereas the Tibetan Plateau receives very little rainfall. In fact, I recently visited the 'wettest place on Earth', Cherrapunji, just south of the eastern Himalayas — it rained! This rainfall pattern is echoed by the distribution of steep slopes in the region. The rain here feeds some of the world's major rivers — the Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong and Yangtze — all carving through the mountains. And although rivers are less efficient at eroding than glaciers, they can still incise landscapes at startling rates. In June 2000, this road in north-west India was undercut and nearly destroyed by a flash flood of the Sutlej River (Figure 5, *opposite top*).

Figure 5 Road in north –west India undercut destroyed by a flash flood of the Sutlej River (photograph taken in May 2001).

Once slopes are undercut, rockfalls such as this example [shown in a slide — Ed.] in Pakistan contribute to the erosion of the mountains. The rivers then act like giant conveyor belts, removing vast volumes of sediment downstream. So, mountains are a bit like lawns: the more you water them, the faster they grow; they are constantly being trimmed off the top; and the faster they are trimmed, the faster they grow! The question is: does erosion keep pace with uplift, or does uplift track changing erosion rates? It is interesting to note that, in the Himalayas at least, the areas of rapid uplift and exhumation of deep rocks occur where major rivers cut through the mountain range: in the two syntaxes at either end of the Himalayas, in the Sutlej Valley and in the Arun Valley in Nepal.

How to break a mountain

So it seems that erosion only encourages mountains to grow. Maybe when continental collision ceases, mountains can gradually be worn down, but is there another way to destroy mountains? Well, Douglas Adams has something to say on this, in this extract from Life, the Universe and Everything:

The ultra-famous sciento-magician Effrafax of Wug once bet his life that, given a year, he could render the great mega-mountain Magramal entirely invisible.

Having spent most of the year jiggling around with immense Lux-O-Valves and Refracto-Nullifiers … he realised, with nine hours to go, that he wasn't going to make it.

So he, and his friends, and his friends' friends, and his friends' friends' friends, and his friends' friends' friends' friends, and some rather less good friends of theirs who happened to own a major stellar trucking company, put in what is now widely recognised as the hardest night's work in history, and, sure enough, on the following day, Magramal was no longer visible.

Effrafax lost his bet — and therefore his life — simply because some pedantic adjudicating official noticed

a) that when walking around the area that Magramal ought to be he didn't trip over or break his nose on anything, and

b) a suspicious-looking extra moon.

Well, for an alternative explanation, we return to Tibet. This plateau is riddled with normal faults — much of the centre of the plateau is extending. There is thrusting around the northern and southern margins (in the Himalayas), and several major strike-slip faults also cross-cut the plateau. It appears that Tibet has a soft centre: the thickened crust of the plateau core is trying to spread outward, like a cowpat sagging under its own weight. In some places, the spreading crust is baulked by solid barriers, such as the Tarim and Sichuan basins; but in others, it spreads out into South East Asia and northern China (Figure 6).

And there are other regions where high plateaux are extending, such as the Basin and Range in North America. This landscape of small, linear ranges separated by basins stretches across a vast area of western America, and represents a region of originally thickened crust that has extended substantially since the Miocene; in fact here, the whole lithosphere has thinned. Yet another region that this process has affected is in the western Mediterranean, between southern Spain and North Africa. This ocean basin used to be a mountain range; in fact, the relics of these mountains lie along the coast in southern Spain and Morocco. It seems that the mountain root was removed, resulting in rapid uplift initially, but then dramatic thinning because the mountains were no longer supported by their root, and spread outward. This collapse was so drastic that the core of the mountain belt subsided below sea level, and now lies under 7km of sediment in the Alboran Sea (Figure 7).

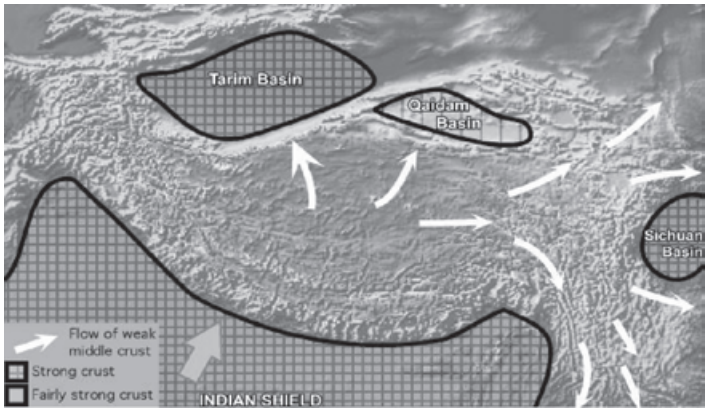

Figure 6 Spreading of the Tibetan Plateau between the Tarim and Sichuan basins (modified from Clark and Royden 2000).

Figure 7 Shani, Karakoram Range, north Pakistan.

So it appears that mountains share a similar opinion of altitude to Francis Younghusband: "A scientific gentleman once asked what was the chief effect of being a long time at high altitudes, and I told him the principal effect was a desire to get to a lower altitude as soon as possible." And I have to say that I, for one, cannot agree, especially when the mountains are as beautiful as this.

Reference

Clark, M. K. and Royden, L. H. 2000 'Topographic ooze: building the eastern margin of Tibet by lower crustal flow'. *Geology* **28** (8), 703–6

Map review

British Geological Survey 2007 *The Assynt Geological Map Sheet* (1:50 000). Keyworth: British Geological Survey (map and booklet £12 + £3 p+p)

This map is based on the Assynt 1-inch Special Sheet of 1923 and includes the results of recent university research and British Geological Survey fieldwork. The new map is at a scale of 1:50 000, so the intricate details of the thrust zone are more clearly seen than on the old map.

The new surveyors have made refinements to the 1923 map but there appear to be few major differences. There are more subdivisions of the Lewisian, but, fortunately for the user, they are given letter symbols rather than various colours. On the other hand, the recently subdivided Torridonian is now represented by garishly coloured units that tend to confuse more than clarify the stratigraphy. The original colour scheme for the Cambro–Ordovician stratigraphic units has been retained: very well chosen in 1923 and still highly appropriate for picking out details in the thrust zone. The new sections give much more realistic interpretations of the thrust zone architecture; and especially useful is the suite of field photographs of key features of the thrust zone.

The 1923 map, based on the fieldwork of Peach, Horne and other members of the Geological Survey at the turn of the century, is probably the best known geological sheet of Scotland and arguably of the UK. It has been used extensively to teach the principles of thrust tectonics, adorned the office wall of many a structural geologist, has panicked many a student undergoing structural practical examinations, and was the basis for huge numbers of field visits by British and international geologists. Such was the deference to the quality of the field study and pioneering work on thrust tectonics that a memorial plinth was erected by the international geological community, poignantly on the Sole Thrust beside Loch Assynt, in tribute to Peach and Horne.

On the new map the lack of recognition of the Geological Survey work in the late nineteenth century is disappointing: one, bland, minor reference. The 1907 Memoir on the NW Highlands, moreover, seems not to be recognised at all. Yet, to quote Dawne Riddle (2007 'Mapping mountains', *Geoscientist* **18**, 7), "The year 2007 was the centenary of the 'Peach and Horne' Memoir to the Geological Structure of NW Highlands, arguably one of the most influential publications on structural geology and tectonics. The maps were a key component of this research and include pioneering 3D representations of thrust belt structure". Also neglected on the new map is an outline of the evolution of the Assynt District, which is essential for newcomers.

The area occupied by the 'Shaded terrane model' panel, which offers little useful information, could be replaced by a summary of the evolution and the Peach and Horne contribution (plus a photo of the memorial plinth). I was duped into buying the 'Exploring the landscape of Assynt' booklet and map set (£12), expecting to find information neglected on the new map. I was wrong. I do not begrudge buying the landscapes set, as it has a different purpose to the new Assynt map (although I resent being charged £3 p&p by BGS when the actual postage cost was 99p!).

— Bill Fitches

Book review

The Cornish Building Stone and Slate Guide 2007. Cornwall County Council (ISBN 9781903798355; looseleaf in ring binder, 81pp; also available on-line at www.cornwall.gov.uk/stoneguide)

This admirable little guide has been produced by Cornwall County Council, as Mineral Planning Authority for the county, to promote the sustainable extraction and use of Cornish building stone and slate.

It has a good 'geological background', and the list of 29 quarry operators is accompanied by a British Geological Survey map on which their locations are shown. There is also a list of more than a dozen salvage and reclamation firms, and an extensive section on stonemasons and dry stone wallers with details of the Guild of Cornish Hedgers, the Dry Stone Walling Association, and the Cornish Hedge Group. Scantle roofing, cob building, lime products, are also dealt with, and details of training courses in various building trades provided, including some outside Cornwall.

Details are also given of relevant national organisations such as the Society for the Protection of Ancient Buildings and the Traditional Building Skills Bursary Scheme. There is a short bibliography, list of useful websites, and contact details for the various Cornwall District Councils and the CCC Historic Environment Service. The booklet is what is usually called 'profusely illustrated', easy to use and a model for what local authorities should be producing.

— Philip Clark MA (Oxon) BSc Hons (Open)

Volcán Teneguia: recent volcanism on La Palma, Canary Islands

Duncan Woodcock

Introduction

La Palma and El Hierro are the two most westerly of the Canary Islands. Both islands are relatively young, with subaerial volcanism dating from *c.* 1.5Ma (Carracedo *et al.* 2001). Both islands display spectacular evidence of the repeated growth and collapse that is typical of the early 'shield-building' phase of development of volcanic ocean islands. El Hierro is currently inactive, with no eruptions in historic times (since the arrival of the Spaniards towards the end of the 15th century). In contrast, La Palma is currently the most volcanically active of the Canary Islands, with frequent activity during the past 125ka along the southern part of the island — the Cumbre Vieja volcano. Six eruptions have occurred in historic times, the most recent activity comprising an eruption of scoria, spatter and lava flows at Teneguia volcano in 1971 (Figure 1).

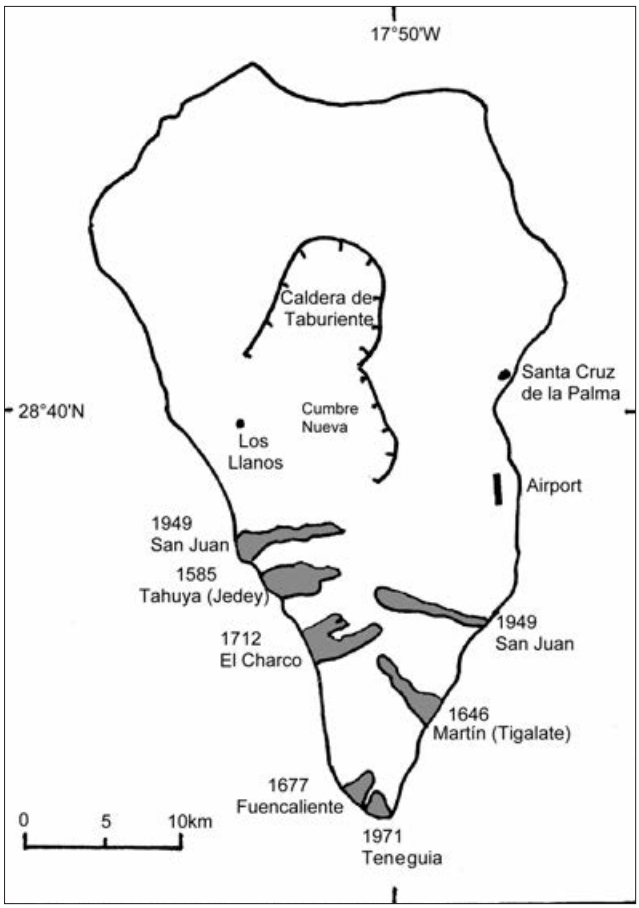

Figure 1 Sketch map of La Palma, showing historical lava flows (shaded areas) along the Cumbre Vieja. The Caldera de Taburiente and the Cumbre Nueva calderas are the remains of giant lateral collapses that occurred earlier in the geological history of the island. Current concerns focus on the possible lateral collapse of the west flank of the Cumbre Vieja.

This paper arose from a visit to Teneguia as part of a longer visit to the Cumbre Vieja area on La Palma in March 2006. It comprises an overview of the eruption, the petrology and geochemistry of the eruption products and a short field guide to areas of particular interest. Teneguia is easily accessible (Figure 2) and contains a range of volcanic features; however, there appears to be little readily accessible material on Teneguia in the literature. A short series of papers on the eruption was published in 1974 as a supplement to volume 30 of Estudios Geologicos. Since then, the area seems to have attracted little attention; the only substantial contribution being a PhD thesis (Praegel 1986).

Figure 2 View of Teneguia volcano from the summit of the San Antonio come (see Figure 4 for location). The lighthouse and salinas *at Faro de Fuencaliente are visible on the coast (top-left of the picture)*

Description of the eruption

The eruption, which lasted from 26 October until 18 November 1971, was carefully observed throughout its duration by Spanish geologists (Araña and Fuster 1974). Seismic precursors began on 15 October and continued until 26 October, when a 200m long N–S-trending fissure opened up. Lava fountaining was observed initially along the whole length of the fissure, but over the next two days activity became concentrated at the ends of the fissure. Activity was particularly intense at the north end of the fissure; this location remained active throughout the entire eruption to build the main volcanic edifice of scoria and spatter known as Teneguia I. Lava flows quickly breached this cone to flow seaward. On 1 November explosive activity immediately to the north of the main cone formed a small circular scoria and spatter crater known as Teneguia III. Subsequently new vents opened on the north side of the main cone. Volcanic activity ceased abruptly on 18 November, although intense fumarolic activity continued for several months. Fumaroles were still active in 1989 (Duncan and Notcutt 1994); activity has all but ceased today.

A total of 40 million cubic metres of lava was erupted (Duncan and Notcutt 1994). The products of the eruption cover much of the area to the south of Teneguia. A total of 3.2km2 is covered by lava flows, including 0.3km2 of new land on the western side where the lava flowed over older sea cliffs and entered the sea (Afonso *et al.* 1974). Areas not covered by lava flows are mantled with lapilli tephra that was carried southward by the northerly winds that predominated during the period of eruption.

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Petrology of the Teneguia lavas

In hand specimen, the Teneguia lavas are dark grey, variably vesicular and sparsely porphyritic with phenocrysts of 1–2mm in a fine-grained groundmass. The phenocryst phases comprise green glassy olivine and at least one black mafic mineral.

In thin section, the olivine phenocrysts are usually euhedral. The black mafic phenocrysts are seen to be clinopyroxene and amphibole. The clinopyroxene phenocrysts are often zoned with a pale brown border and a greenish core. The amphibole phenocrysts exhibit a light brown–dark brown pleochroism.

A comprehensive petrographic study of the sequence of lavas (Fernández *et al.* 1974) showed that amphibole was the most abundant phenocryst phase in lavas erupted before 11 November but that olivine phenocrysts predominated after that date.

The lavas are locally rich in a variety of mafic and ultramafic inclusions. These are 5–30mm in size and range in shape from angular to rounded. All inclusions have sharp margins against the host basalt. In some cases, the basalt has pulled away from the margin of the inclusion, leaving an elongate cavity.

The mafic inclusions have a gabbroic texture and comprise an intergrowth of clinopyroxene and plagioclase. Praegel (1986) considers these to be fragments of oceanic crust. The ultramafic inclusions are of two main types: greenish glassy inclusions that consist almost entirely of olivine, and black inclusions. In thin section these black inclusions are mineralogically quite complex, comprising clinopyroxene and yellow-brown pleochroic amphibole together with minor amounts of olivine, biotite and an opaque mineral.

Muñoz *et al.* (1974), show that the occurrence of mafic and ultramafic inclusions increased towards the end of the eruption; presumably because magmas from deeper in the crust and mantle were being erupted then.

Geochemistry of the Teneguia lavas

Ibarrola (1974) presents major element analyses for 28 basalt samples spanning the whole period of the eruption. Figure 3 shows a plot of the variation of wt % SiO2 for these samples arranged in date order. There is a clear discontinuity between samples 15 and 16, a pattern that is repeated for most of the other major elements. The discontinuity occurs on 11 November and coincides with the change in modal mineralogy reported above; it confirms that there was a significant change in the magma chemistry at that time.

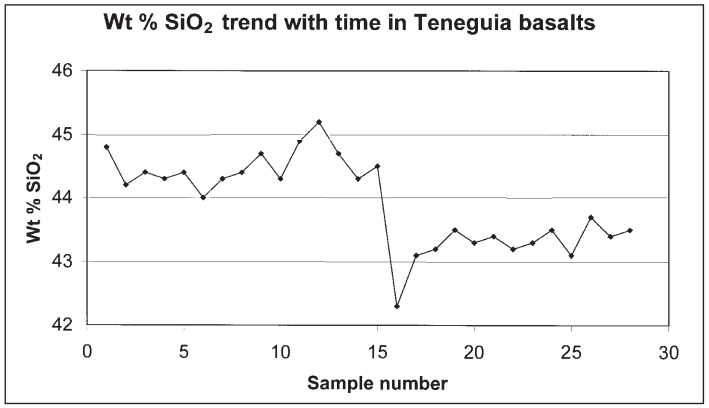

Figure 3 Variation of wt % SiO_2 for basalt samples from the Teneguia eruption arranged in order of eruption (data from Ibarrola 1974).

Some basalt samples erupted before 11 November were found to contain small xenoliths of partly fused phonolite. On the basis of these Ibarrola speculated that the magma erupted before 11 November had been produced by the assimilation of a pre-existing phonolitic rock by a magma with a composition represented by the post-11 November lavas, but did not test this hypothesis quantitatively. His speculation was supported by the field evidence from the 1585 eruption at Jedey, where large xenoliths of phonolite are abundant in the lavas erupted.

A phonolite body, the Roques de Teneguia, crops out about one kilometre to the NW of Teneguia volcano and this may be the source of the assimilated material in the pre-11 November Teneguia lavas. Four major element analyses of the Roques de Teneguia material are now available (Hernández-Pacheco and de la Nuez 1983), providing the opportunity to test the assimilation hypothesis quantitatively.

Table 1 contains the mean composition of the pre- and post-11 November Teneguia lavas, together with the data for the Roques de Teneguia.

Table 1 Major element analyses (wt % oxide) for the Teneguia basaltic lavas (from Ibarrola 1974) and the Roques de Teneguia phonolite body (from Hernández-Pacheca and de la Nuez 1983).

	pre-11 Nov Teneguia	*post-11 Nov Teneguia*	*Roques de Teneguia*
SiO_2	44.49	43.27	54.75
Al_2O_3	15.44	13.68	20.20
Fe_2O_3	4.38	3.92	2.81
FeO	7.96	9.39	1.38
MnO	0.22	0.22	0.14
MgO	7.18	9.22	0.98
CaO	9.19	10.28	3.25
Na_2O	4.33	3.61	9.31
K_2O	1.80	1.46	4.64
TiO_2	3.61	3.63	0.90
P_2O_5	0.98	0.88	0.23
H_2O	0.25	0.19	0.75
totals	99.83	99.75	99.34
FeO_t	11.90	12.92	3.91

The data in Table 1 can be used for a quantitative test of the assimilation hypothesis as follows. Suppose that a mass fraction N of the average Roques de Teneguia material has been assimilated into a mass fraction (1-N) of average post-11 November Teneguia magma to produce the pre-11 November magma. A mass balance for any major oxide component is thus:

$$RN + B(1-N) = A \qquad (1)$$

where:

R = wt% of component in average Roques de Teneguia material

B = wt% of component in average post-11 Nov Teneguia magma

A = wt% of component in average pre-11 Nov Teneguia magma

Values for N may be calculated for each major oxide; these are contained in Table 2 *(opposite top)*.

The large negative value of N for Fe2O3 is infeasible, suggesting that during assimilation some oxidation of FeO to Fe2O3 occurred. For the mass balance calculations it is probably more appropriate to use the value of N for FeOt, the total iron (as equiv-

Table 2 Values of N, the mass fraction of phonolite assimilated by the Teneguia magma, calculated from equation (1).

oxide	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	FeO_t
value of N	0.11	0.27	-0.41	0.18	0.00	0.25	0.16	0.13	0.11	0.01	-0.14	0.11

alent FeO). The data supports the assimilation hypothesis and is consistent with *c.* 10 to 20% assimilation of phonolitic material into the original magma.

In principle it is possible to calculate a 'best fit' value of N, using a least squares algorithm with an appropriate objective function. In practice it is more profitable to consider whether it is feasible for the original magma to melt 10–20% of its own weight of phonolite. Thermal data relevant to this heat balance (Spera 2000) is summarised in Table 3.

Table 3 Thermal data for selected igneous rocks(from Spera 2000).

	latent heat kJ/kg	*specific heat kJ/kgK*	*liquidus temperature*
gabbro	396	1.48	1200C
granodiorite	354	1.39	1100C
granite	300	1.38	1000C

For illustrative purposes, the basaltic magmas are modelled as liquid gabbro and the phonolite modelled as solid granodiorite at 500C. The temperature drop, ΔT, of the basaltic magma during the assimilation of a mass fraction of 15% phonolite can be estimated as follows:

Heat lost by the
basaltic magma = (1-0.15) * 1.48.*.ΔT kJ/kg (2)
Heat gained by the
phonolite = 0.15(1.39 * (1100-500) + 354)) kJ/kg (3)

For adiabatic assimilation, the heat lost and heat gained are equal. The corresponding value of ΔT is thus *c.* 140C; this is a maximum value, which assumes that the magma remains at or above the liquidus. Note that the assimilated phonolite is wetter and of higher alkali content than the original magma; this may have been sufficient to depress the liquidus temperature by 140C.

Outline field guide to the Teneguia area

The Teneguia area is covered very briefly in recent field guides (Carracedo and Day 2002, Duncan and Notcutt 1994). Figures 4 and 5 have been prepared to supplement this material, and should be largely self explanatory. A wide range of volcanic products can be inspected at close hand in the area immediately adjacent to the main volcanic edifice (Figure 6, *overleaf*), including the Teneguia III crater (Figure 7, *overleaf*), accretionary lava balls and spatter walls (Figure 8, *overleaf*) and aerodynamically shaped volcanic bombs (Figure 9, *overleaf*). The footpath that runs east and then south from the Teneguia III crater crosses one of the main lava flows and then continues down to the Faro de Fuencaliente on the southern tip of La Palma. Adjacent to the Faro is a large *salina*, where salt is produced from seawater by evaporation in open ponds. Much of the rock used in the con-

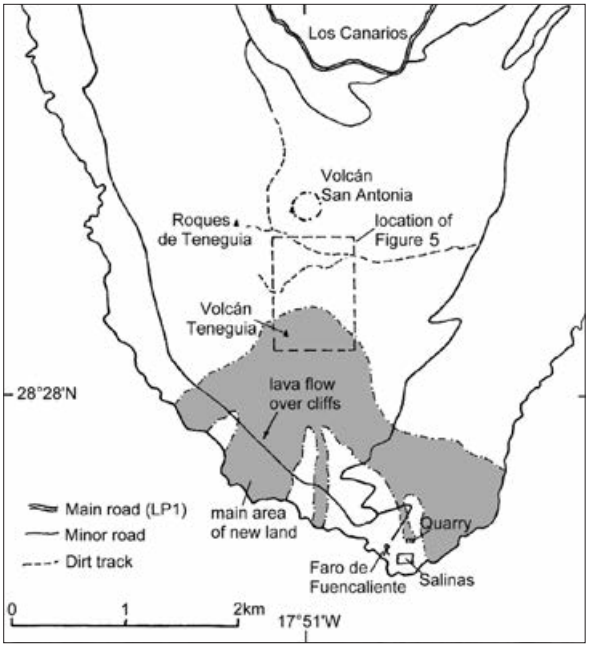

Figure 4 Sketch map of the south end of La palma, showing the main areas covered by lava flows (shaded areas) from the Teneguia eruption.

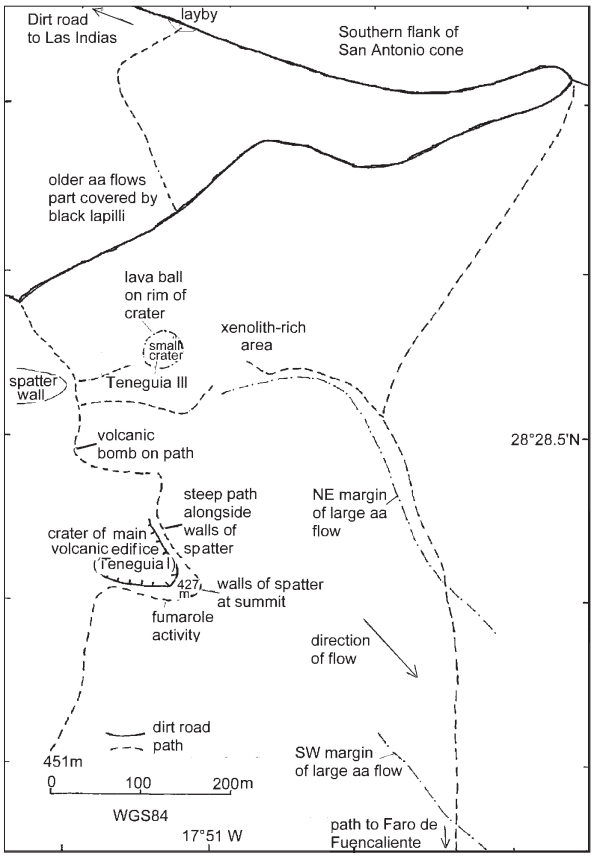

Figure 5 Sketch map of the area in the vicinity of Teneguia, showing the locations of easily accessible volcanic features of interest.

struction of the ponds came from a quarry in the toe of a lava flow immediately to the north of the ponds. The lavas in this quarry are particularly rich in mafic and ultramafic xenoliths (Figures 10 and 11–12 *opposite*).

Figure 6 View of the main volcanic edifice (Teneguia I) from the layby marked on Figure 5. The small crater in the foreground is the Teneguia III centre.

Figure 7 View of the Teneguia III crater from the lower slopes of the main edifice. Note the accretionary lava balls in the foreground and the prominent one on the rim of the crater at the 10 o'clock position.

Figure 8 The large accretionary lava ball on the rim of the Teneguia III crater. The crater wall comprises c. *5m in vertical height of scoria and spatter.*

Figure 9 A volcanic bomb with a fluted tail shaped by the flow of the air around the semi-liquid bomb during flight.

Postscript: the wider significance of the Teneguia eruption

The 1971 eruption of Teneguia volcano is the most recent of a long series of eruptions along the Cumbre Vieja ridge and thus contributes to the growth phase of La Palma. The eruptive products that are so well displayed along the Cumbre Vieja have subterranean intrusive counterparts that are wedging apart the ridge. During the 1949 eruption, parts of the Cumbre Vieja ridge developed a west facing normal fault system (Day *et al.* 1999): there is thus concern that the Cumbre Vieja may be in a state of incipient collapse. Although no additional movement was observed on these faults during the Teneguia eruption, future eruptions along the Cumbre Vieja may precipitate a collapse and a possible megatsunami.

Acknowledgements

I wish to thank the management of the Salinas de Fuencaliente for access to their quarry in the toe of the 1971 lava flow.

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Figure 10 A pyroxenite ultramafic xenolith — Salinas de Fuencaliente.

Figure 11 An olivine xenolith — Salinas de Fuencaliente.

Figure 12 A gabbro xenolith — Salinas de Fuencaliente.

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Book review

M. F. Howells 2007 *British Regional Geology — Wales*. Keyworth: British Geological Survey (ISBN 0 85272 584 9; paperback, 230pp (with detachable map); £18)

Wales now joins the small number of areas of Britain with brand new Regional Geology Guides, not new(ish) editions of the increasingly hard-to-use old series. This excellent and attractive volume replaces the old division into North and South Wales, which "the pattern of geology across the Principality and beneath the adjacent sea bed makes it difficult to maintain"; increased knowledge of the sea floor around Wales is, along with the theory of plate tectonics, the main new factor in understanding Welsh geology since the first BRG guides). Maps, figures, tables and photographs are now in colour, which makes the price impressive, as there is a map, figure or photograph on almost every page.

Although the volume is little longer than the two previous ones together, many formations are described at impressively greater length, for example the Brownstones, Plateau Beds, Grey Grits and Quartz Conglomerates that cap the Old Red Sandstone sequence. I think this is because depositional environments and fossil fauna have been so intensively studied in the last two generations.

There is a full introduction, including a history of geological research from the early days of geology to the present, amply bearing out the assertion that "Wales has had an influence in the history of geology that is inversely proportional to its size", and a brief review of its geotectonic setting through the ages. Chapters follow on the Precambrian and on each period from the Cambrian to the Carboniferous, while the Mesozoic and Cainozoic have but a chapter each, reflecting the comparative paucity of cover from these eras. The discussion of 'Palaeogene–Neogene' (formerly Tertiary "now an obsolete term") uplift is circumspect and although stating that it "was probably dome-like" does not mention the opening of the North Atlantic as possibly involved. Lack of Cainozoic cover, except in offshore basins, makes this a notoriously difficult subject.

Every so often a section on a particular topic is inserted into the sequence of series or stages: Ordovician volcanism, Caledonian orogeny, Variscan orogeny, mineralisation, oil and gas. An excellent short chapter on 'Geology and Man' closes the volume, dealing with building stones and industrial exploitation from the earliest times of human habitation to the present. There is a full bibliography (particularly rich on the Carboniferous).

I cannot imagine anyone with geological interests having the good fortune to live in the Principality or to visit it regularly who would not want to possess this volume!

— Philip Clark MA (Oxon) BSc Hons (Open)

Field Observations in the Old Red Sandstone of the South Pembrokeshire coastline

John Downes

The Old Red Sandstone (ORS) rocks of South Pembrokeshire represent molasse deposits produced by erosion following the Caledonian orogeny. During the Devonian Period in South Wales, continental style sedimentation took place in a semi-arid mountainous landscape in which braided streams laid down thick conglomerates and sandstone/mudstones sequences were deposited by meandering rivers. There are differences in the ORS stratigraphy on either side of the Ritec Fault (Figure 1, *opposite*). While correlation of the Lower Devonian beds is possible across the fault, during the Upper Devonian Epoch uplift and erosion occurred in the north, whereas the Skrinkle Sandstone Group was deposited at this time in the south. Thus the incipient growth of the Ritec Fault during the late Devonian appears to have played a significant role in controlling sedimentation. However, the influence of Variscan tectonic structures is manifest in the ORS strata, imparting a characteristic E–W trend to the fold axes such as the Castlemartin Corse anticline and the Pembroke syncline.

The ORS is a continental facies of the Devonian Period and in Pembrokeshire it lies unconformably on the eroded surface of the Silurian strata; a well defined lithological break in the rock succession. Traditionally the base of the Devonian has been identified by the Ludlow Bone bed in the Welsh borderland, where the ORS sequence of the Downtonian and Dittonian Series is developed. However, since 1972, a new boundary has been designated using palaeontological evidence from the marine facies in Europe. The base of the Devonian Period is now considered to be near the top of the Downtonian, so that in Pembrokeshire it lies within the Moor Cliffs Formation.

The following selected localities illustrate the major characteristics of the ORS where it is exposed along the shoreline and is accessible from the coastal path. Note that localities 1–5 lie to the south of the Ritec Fault and that localities 6 and 7 are to the north of the fault (Figure 2).

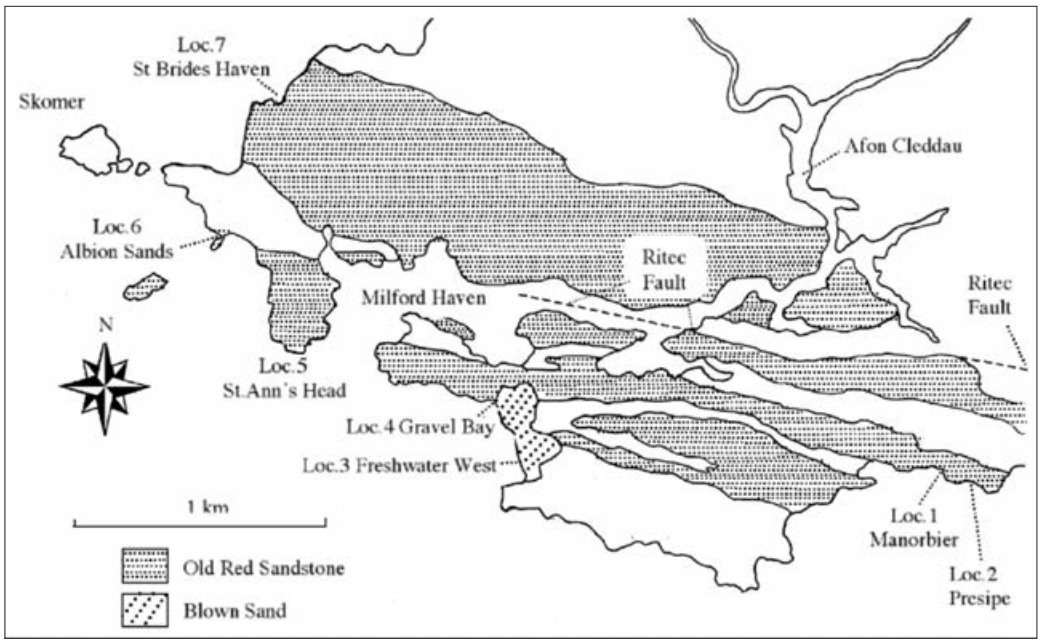

Figure 2 Old Red Sandstone outcrops in South Pembrokeshire.

Location 1 Manorbier

Manorbier (SS066978) can easily be reached via the B4585 from the main Pembroke–Tenby road. There is a large car park near the castle and adjacent to the beach. Take the cliff path on the east side of Manorbier Bay and make for the cromlech known as King's Quoit, where a deep indentation in the cliffs marks the junction between the Moor Cliffs Formation and the overlying Freshwater West Formation (Figure 3, *page 12*). Looking across the bay from King's Quoit, one can clearly see the strike (285/105°) of the sandstone ribs on the foreshore. There is a steep dip NNE towards the axis of the Pembroke syncline. Continue to Priest's Nose, where there are several deep recesses eroded along the line of tuff bands, which are obviously much less resistant than the adjacent sandstones. Follow the path eastward for about 400m to Rook's Cave (SS062971). This is a deep faulted cleft crossed by three prominent airfall tuffs that follow the strike of the rocks (Figure 4, *page 12*). The most southerly of these is known as the Rook's Cave tuff, which is about 0.7m thick.

It is possible to reach the next locality at Presipe by continuing along the coast path for about 1km; alternatively return to the car park and drive east through Manorbier village. Turn left at the Ministry of Defence (MOD) married quarters and continue down the road to the entrance to Manorbier Camp.

Location 2 Presipe

Presipe (SS069970) is the name of the bay immediately to the west of Old Castle Head. Parking is available on the roadside near the main entrance gates of Manorbier Camp (SS075974]. Follow the coastal path in a south-west direction around the boundary of the MOD firing range. The beach is accessed at Presipe down a steep flight of steps that follows approximately the line of a major dextral tear fault with a displacement of 250m. This brings the Moor Cliffs Formation on the west side of the bay into contact with the Conigar Pit Sandstone Member, which outcrops to the east of the fault.

These rocks strike across the bay with a dip of *c.* 85° NNE. The steep bedding surfaces display a variety of sedimentary structures associated with an arid environment in which mud and sand were drying out. Near the base of the steps there are sand-filled pipes 100mm in diameter that stand proud of the sandstone bedding plane. These are soft sediment features that were probably formed by rising ground water; but since undergoing lithification, the pipe infill has become harder than the surrounding sandstone. Walk around into the large recess *c.* 50m east of the steps and a massive slab exposes a magnificent rippled surface, evidence of shallow water currents.

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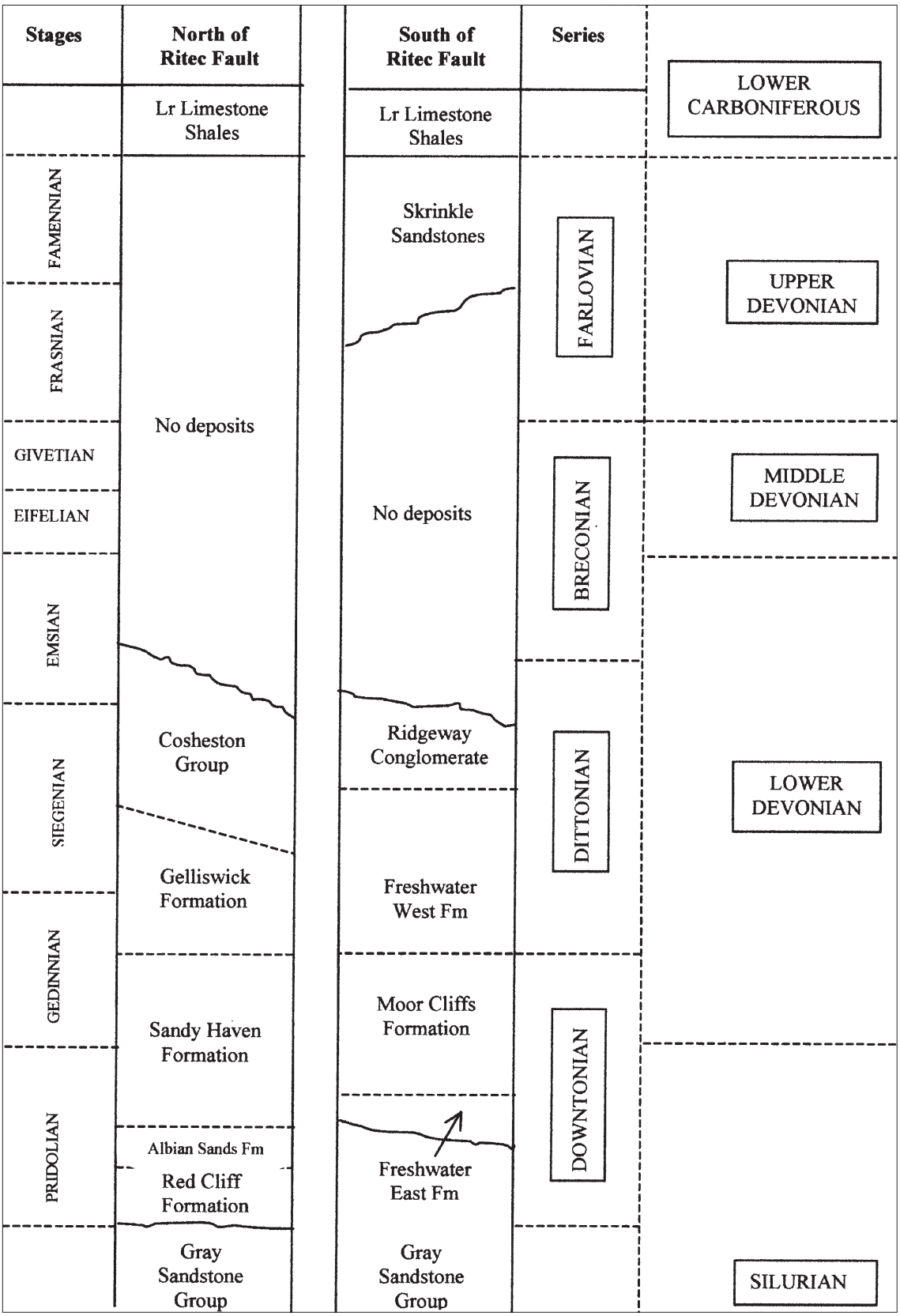

Figure 1 Stratigraphical column for the Old Red sandstone in Pembrokeshire.

Note that this ripple formation represents an overlying sandstone mould as the beds are younging to the north.

In the centre of the bay there are several large bedding planes showing mud-filled polygons where the cracks are preserved in carbonate material. An excellent cross section through a sequence of upward-fining cycles can be seen where the small valley of Water Come On (SS072968) enters the bay. Each cycle consists of pebble-sized conglomerates, sandstones and mudstones with calcrete beds. The conglomerates are intraformational and they rest on well defined scoured surfaces. These repeated fining-up sequences are the successive deposits of a meandering river system bordered by a wide floodplain where overbank silts and lacustrine muds became desiccated in the desert climate.

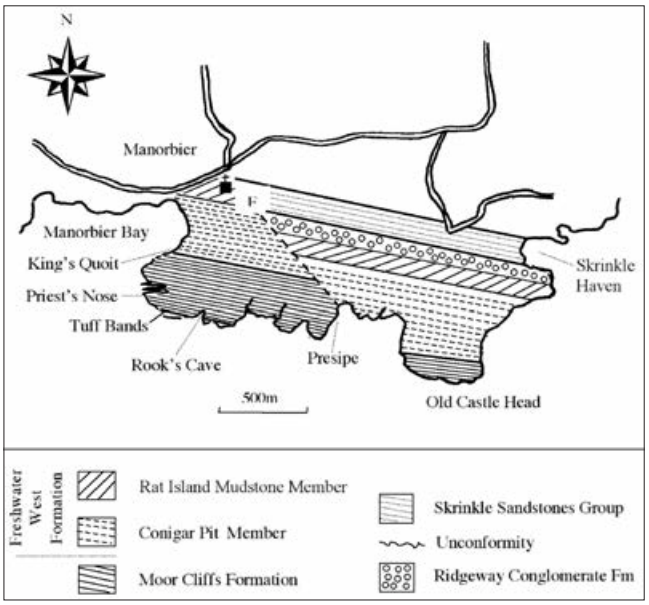

Figure 3 Geology of Manorbier.

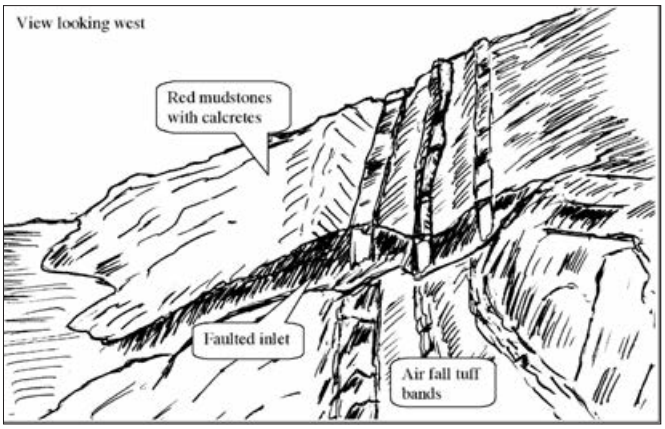

Figure 4 Rook's Cave, Manorbier.

Location 3 Freshwater West

Freshwater West can be approached from Castlemartin village along the B4319. There is a car park at Gupton Burrows [SR886998], adjacent to the coastal road. A good view of the whole foreshore section can be obtained from the top of Little Furzenip, which is only *c.* 30m from the car park (Figure 5).

On the foreshore, there is a sequence of steeply dipping strata younging southward on the south flank of the Castlemartin Corse anticline. At the northern end of the section there are *c.* 11m of marine Silurian siltstones and sandstones belonging to the Gray Sandstone Group (Wenlock age). The basal ORS conglomerate beds known as the Freshwater East Formation lie unconformably on the scoured surface of the Silurian sediments. However, these beds and much of the succeeding Moor Cliffs Formation are difficult to observe in detail owing to the thick growth of seaweed and barnacles obscuring them. (They are much better exposed at Locality 4). It is therefore more productive to start one's examination of the rocks on the south side of Little Furzenip headland, where red and green mudstones with multiple calcrete profiles are exposed near the top of the Moor Cliffs Formation. These pedogenetic carbonates display nodules, concretions, tubules and festoons, which form under arid conditions when calcium rich groundwater is drawn to the surface

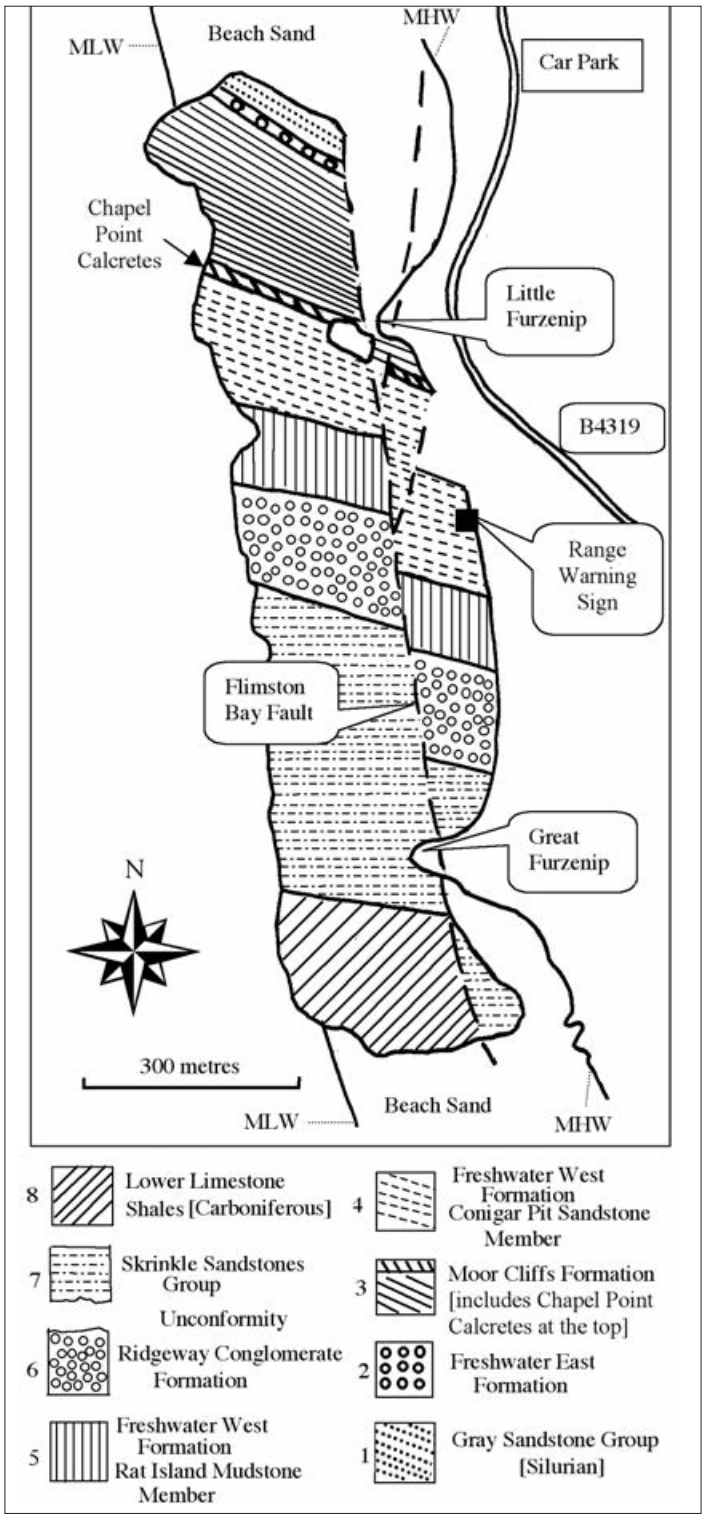

Figure 5 Geology of Freshwater West Formation.

by capillarity (Figure 6, *opposite top*). The carbonate horizons were referred to as 'cornstones' by 19th-century geologists and were described as concretionary chemical limestones. The multiple calcrete profiles at the top of the Moor Cliffs Formation are known as the Chapel Point Calcretes after the type section on the south coast of Caldey Island where there is a comparable ORS sequence to that at Freshwater West.

Note that the Flimston Bay Fault bisects the whole succession of beds on the foreshore. It is a dextral tear fault with a displacement of *c.* 120m and is responsible for isolating Little Furzenip stack from the headland.

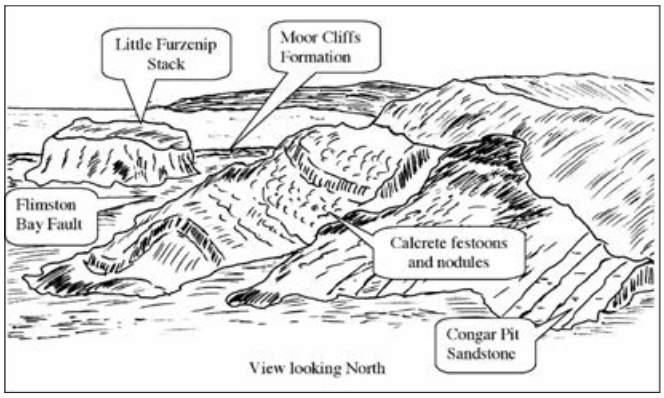

Figure 6 Chapel Point Calcretes at Little Furzenip.

The succeeding Freshwater West Formation (Dittonian Stage) is 345m thick and is well exposed to the south of Little Furzenip — east of the tear fault. The red mudstones and sandstones of this formation are rich in ferric oxide formed under oxidising conditions in the dry desert atmosphere. The green-coloured layers are indicative of the presence of water that reduces the red ferric oxide to ferrous oxide. The lower sequence is the Conigar Pit Sandstone Member and forms a series of upward-fining cycles consisting of conglomerates, sandstones and calcareous mudstones. These are best examined in the vicinity of the MOD range warning sign. There are some excellent examples of ripple drift bedding, graded bedding and cross stratification in the fine-grained grey sandstones.

Trough cross stratification is typical of point bar deposits in a meandering river where the sediments fine upward from lag gravels overlying a scoured surface. The process of lateral accretion builds up the point bar with the current direction being at right angles to the slope of the cross stratified beds. The term epsilon cross stratification is applied to this type of lateral accretion in contrast to deltaic or shallow marine cross stratification where the current direction is parallel to the depositional slope.

Approximately 15m south of the Range Warning Sign there is a distinctive bioturbated light grey sandstone *c.* 1.5m thick, which is known as the Beaconites bed (see Figure 5a). Large burrows of Beaconites barretti occur perpendicular to the sedimentary layering. Some burrows are up to 300mm deep and 100mm in diameter — tapering downward and filled with fine sand — making a good 'way up' structure for the geologist. It is considered that the burrows were excavated by early Devonian terrestrial arthropods burrowing into soft overbank sediments of ephemeral streams in a semi-arid environment.

The upper sequence of the Freshwaterwest Formation is known as the Rat Island Mudstone Member and is dominated by ripple-bedded red mudstones and calcrete beds, which outcrop between 100m and 150m south of the range warning sign.

The Ridgeway Conglomerate Formation (115m) contains extra-formational conglomerate horizons with sharp erosional bases interbedded with red sandstones and siltstones. The clasts of quartzite, greywacke and phyllite appear to have been derived from Lower Palaeozoic source material from the south and laid down in braided rivers and alluvial fans in a semi-arid environment.

The unconformable junction between the Ridgeway Conglomerate at the top of the Lower Devonian (Dittonian), and the overlying Skrinkle Sandstone Group occurs at SR887989, *c.* 180m north of Great Furzenip. Although there is no obvious angular discordance at the boundary, there is a distinct facies change from the conglomerates to a fine-grained sandstone in which the scales of the Crossopterygian ganoid fish Holotychius have been found. It is on this palaeontological evidence that the Skrinkle Sandstones are considered to be of Upper Devonian age (Farlovian Stage).

The basal fine sandstones are succeeded by distinctive light-coloured quartzites and a thick conglomerate member in the cliffs around Great Furzenip headland. However, to the west of the tear fault on the wave cut platform, the Skrinkle Sandstones pass conformably into the Lower Limestone Shales (Lower Carboniferous). But please note that it is not advisable to proceed beyond Great Furzenip as there may be activities taking place on the Castlemartin firing range.

Location 4 Gravel Bay

This bay is located *c.* 1km NNW of the Freshwater West section, and can be approached from the car park (SM885004) at Broomhill Burrows alongside the B4319. The ORS sequence that outcrops here is on the northern flank of the Castlemartin Corse anticline. On the foreshore between two tear faults there is a 30m section that exposes the Gray Sandstone Group (Wenlock age), overlain by the basal conglomerate of the Freshwater East Formation that forms upstanding resistant outcrops dipping at 60° NE and striking parallel to the main anticlinal axis (Figure 7).

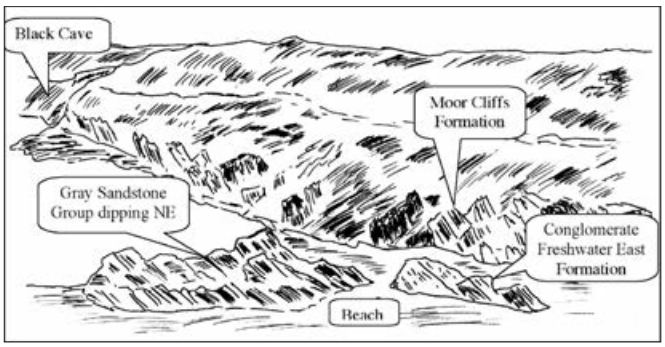

Figure 7 Gravel Bay looking north-west.

The conglomerate is extra-formational, containing clasts of Silurian sandstone together with quartz cobbles up to 100mm across. The succeeding Moor Cliffs Formation is well exposed in Gravel Bay where thick red mudstones, cross-stratified sandstones and calcretes are present. This formation outcrops along the south coast of the Angle peninsula for several kilometres.

Follow the coastal path westward to Black Cave (SM871008), where the Moor Cliffs Formation is dipping at about 50° N. The pathway follows the approximate direction of the E–W strike of the rocks. At Black Cave there is a series of red mudstones and interbedded calcretes with several prominent grey-green sandstones. Continue onward for *c.* 500m to East Pickard Bay (SM865010), where there are several tuff bands that form distinctive marker horizons within the Moor Cliffs Formation (Figure 8, *overleaf*).

In order to examine these rocks at beach level, it is necessary to leave the coast path and scramble down to the rocky foreshore on the east side of the bay. This should only be attempted at low tide to avoid being cut off by a rising tide in the steep-sided bay. The two most important bands are the Townsend Tuff and the succeeding Pickard Bay Tuff, which are separated by *c.* 20m of calcretised red mudstone. The Townsend Tuff can best be examined

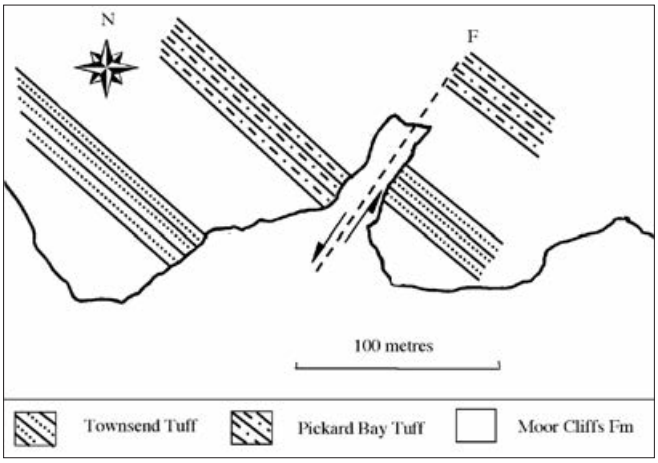

Figure 8 East Pickard Bay.

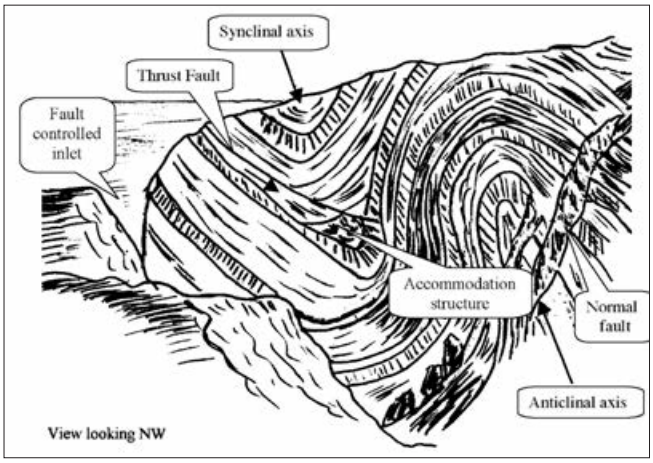

Figure 9 Cobbler's Hole, St. Ann's Head.

in the eastern side of the bay, whereas the Pickard Bay Tuff outcrops on the western side; but note that a sinistral wrench fault bisects the bay and offsets the strata by some 50m. Both tuffs consist of three fining-upward units with a coarser lithic tephra at the base grading up into a dust tuff at the top.

These horizons are considered to be airfall deposits produced by contemporaneous volcanic eruptions during the Lower Devonian (Downtonian Stage).

Location 5 St Ann's Head

The headland (SM806028) can be approached by the B4327 to Dale village; then follow the narrow lane to the National Trust car park at SM803042, which is *c.* 1km north of St. Ann's Head. Walk through the small hamlet of Kete, then turn right and take the footpath across the fields to the Frenchman's Bay. Here the Freshwater West Formation dips steeply north, as the strata lie on the southern flank of the Pembroke syncline. Follow the cliff path around the bay to the south side where the beds dip directly into the sea. During winter storms, when the bedding planes are well lubricated, this area is subject to rock slides.

Continue to The Vomit where the path joins the road to St. Ann's Head, and walk down to the South East side of Cobbler's Hole to view a fold couplet where accommodation structures are well displayed (Figure 9). Compression on the inner fold arcs and extension on the outer arcs has resulted in flexural slippage between the beds. There is a thrust fault in the nose of the syncline that breaks into the hinge line. Cleavage is developed convergent to the axial planes and is refracted near the core of the fold. The eastern limb of the anticline is cut by a normal fault that downthrows to the east.

Location 6 Albian Sands

These sands (SM772076) should be visited on the ebb tide, when it is possible to walk across to Gateholm Island from the mainland. There is a National Trust car park (SM772077) near Runwayskiln Farm, which is approached along the narrow road from Marloes village.

Take the bridle track that runs south-west from the car park entrance; it is signposted to a youth hostel. Continue along the track past the Nature Reserve at Marloes Mere and then bear left along the footpath leading to the coast. A path descends steeply to the beach at SM772077, where the cliffs project towards Gateholm Island. The oldest ORS rocks in Pembrokeshire are exposed on the foreshore in the Red Cliff Formation (Downtonian) where the beds dip steeply SSE, as here we are on the northern flank of the Pembroke syncline (cf Locality 5). The base of the formation rests directly on the Gray Sandstone Group of the Silurian inlier that forms the Marloes peninsula. There are *c.* 50m of red mudstones and interbedded calcretes with cross-stratified, fine sandstones, representative of a floodplain environment that from time to time dried out to produce mud cracks and calcrete deposits.

A metre thick air-fall tuff marks the junction with the succeeding Albian Sands Formation (110m thick), which contains numerous buff-coloured conglomerate beds that can be examined at the base of the cliffs around Horse Neck near where the path reaches the beach. Fining-upward sequences occur with conglomerates above erosional bases, grading into cross stratified sandstones and mudstones. Some of the conglomerates contain sandstone clasts 400–500mm across. Such beds are characteristic of flash floods bringing down debris from nearby mountain regions. Several darker-coloured igneous pebble conglomerates can be identified in the vicinity of Gateholm Stack providing evidence of volcanic activity in the area.

The most spectacular structural features are the conjugate shear zones containing en echelon quartz veins, which can be seen on the sandstone bedding planes around Horse Neck. The tension gashes were opened up as the rock mass moved in opposite directions on either side of a brittle shear zone, in response to compression created by the Variscan earth movements. These arrays of extension fractures were later infilled with quartz. In some cases sigmoidal tension gashes have developed because of rotational shearing (Figure 10, *opposite*).

The overlying Sandy Haven Formation can be examined on Gateholm Island, where there are numerous thick mudstone units with calcretes and some quartz pebble conglomerates with sharp erosional bases.

Location 7 St. Brides Haven

This location (SM802110) lies on the west coast *c.* 3km north of Marloes village. There is a small car park next to the church overlooking the haven. It is necessary to visit this locality at low tide, as most of the interesting structural features are exposed on the foreshore (Figure 11, *opposite*). The mudstones and sandstones of the Sandy Haven Formation dip gently southward at around 10° and are cut by numerous dextral strike-slip faults running approximately N–S across the foreshore. Several smaller splay faults can also be seen. The position of the main faults is marked by narrow

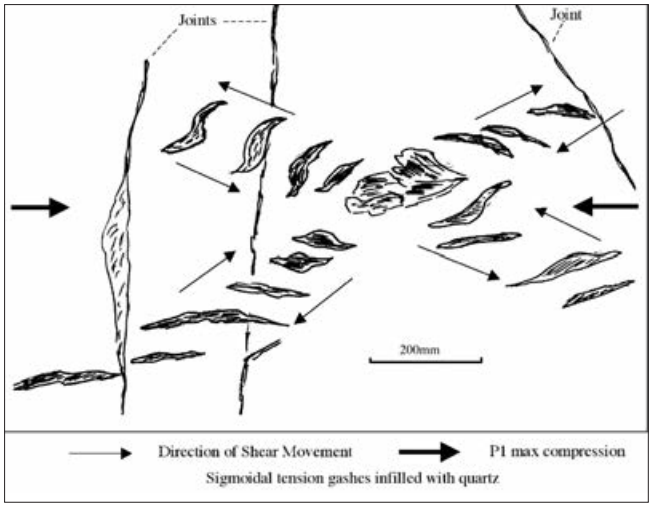

Figure 10 Conjugate shear zones with sigmoidal gash veins in the Albian Sands Formation.

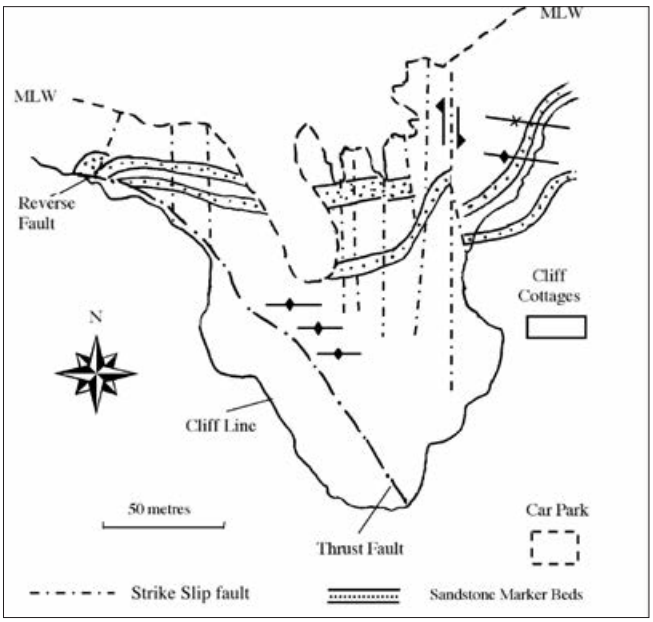

Figure 11. Structural map of St. Brides Haven.

gullies where the sea has eroded along the lines of weakness. The most obvious fault can be seen on the east side of the haven, where the sandstone marker beds are offset dextrally by *c.* 20m. These marker beds can easily be identified in the cliff face *c.* 50m north of Cliff Cottages. The lowest bed is a grey-brown micaceous sandstone with a conglomeratic base. It is separated from the overlying sandstone marker by *c.* 3m of red cleaved mudstone. A useful exercise is to trace these faulted marker beds across the foreshore, but in many places the rocks are heavily encrusted with barnacles and this often makes identification difficult.

The sandstones in the cliff face display a gentle symmetrical fold couplet with axes gently plunging eastward. The straight limbs are cut by several conjugate contraction faults, where the amount of shortening can be measured on the fault planes. Note that axial planar cleavage occurs within the mudstones of the fold but is absent from the coarser sandstones. Another sequence of three tight-fold couplets with the same orientation occurs on the south-west side of the foreshore.

Finally walk over to the NW side of the haven where the marker beds can be traced to the foot of the cliffs. Here there is a prominent reverse fault running NW–South East across the foreshore to the head of the bay (Figure 12). The beds to the south-west of the fault form the hanging wall that has been pushed up over the footwall on the NE side — a classic case of crustal shortening.

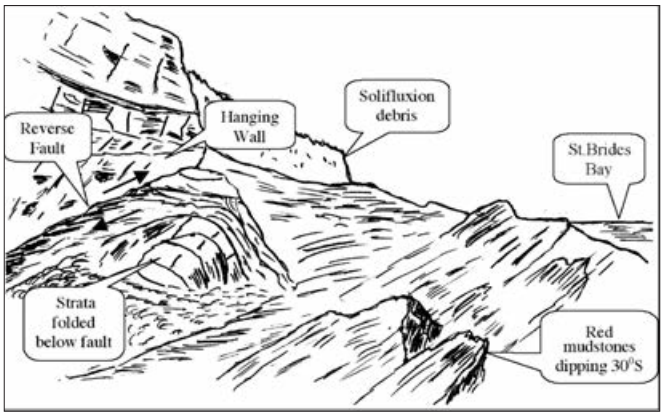

Figure 12. St. Brides Haven west side.

Maps

Geological Survey 1:50,000, Sheet 226/227, Milford

Geological Survey 1:50,000, Sheet 244/245,Pembroke and Linney Head

Ordnance Survey 1:25,000 Outdoor Leisure, Sheet 36 South Pembrokeshire

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Fun with an incident light microscope

Mike Friday

The idea

While writing about a trip to North Wales, which included gold panning in the River When, the idea came to me of photographing one of the tiny specs of gold. This would add reality to the otherwise vague notion of the pursuit.

Although not possible at the time owing to a lack of equipment, this project has now been completed and many thanks are due to Linda McArdell for providing me with a first class sample to work with. However, a speck of gold from a pan cannot be photographed with an ordinary camera, hence a USB type, specifically designed for and attached to a microscope, was used (Figure1).

Addressing the problem

Microscopes have an especially small depth of field, typically only a fraction of a millimetre at a magnification that would enable the whole of the object to be contained in the frame. From the first attempted photograph, clearly only the upper surface of the flake is in focus (Figure 2); whereas the pits, hollows and sides remain blurred (Nelkon and Parker 1961).

Figure 1 Microscope with USB attachment.

An iris had to be added to the system to increase the objective f-number.

As any photographer knows, the f-number is the focal length/aperture or f/D. In the case of a microscope, the calculations are centred on the objective lens, whereas with a camera, a single virtual lens represents the whole system. A disc cut from thin cardboard sheet to match the internal diameter of the lens mounting had a hole accurately punched at its centre. Great care was taken not to abrade the objective (normally its cleaning is done with a lens cloth or brush for this reason).

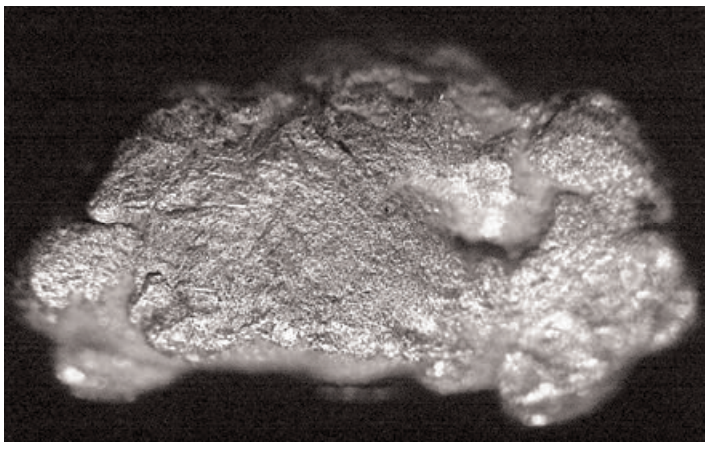

Figure 2 (above) Gold flake 2.5mm × 1.4mm.

The theory

Now, f/D is true for subjects at infinity and can be approximated in a camera; but this is not true where an object is very close to the objective lens.

So, in the case of the microscope, something called a working f-number f_w is required, where,

$$f_w = \frac{1}{2\times NA}$$

NA being the numerical aperture of the lens (Wikipedia 2008a, 2008b).

For the microscope, $NA = n\sin\theta$ where θ is ½ the angle subtended by the lens at the object O and n is the refractive index of air = 1 (because sometimes the system may be in another medium) (Figure 3).

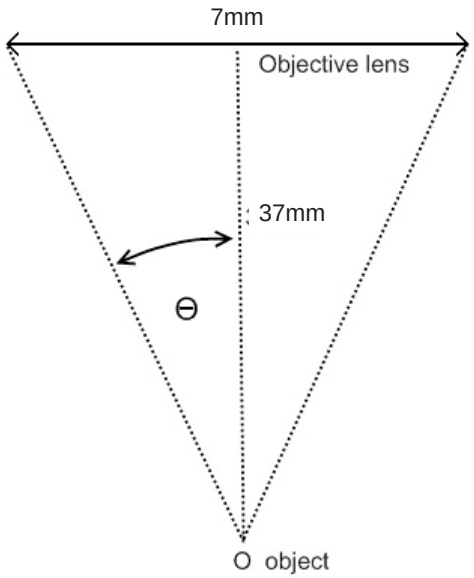

Figure 3 Diagram for calculating numerical aperture (NA): unstopped objective.

By measurement, the diameter of the lens was 7mm. At focus, the lens object distance was found to be 37mm with the 4× objective.

Thus using NA = $n\sin\theta$, then $NA = 1\sin\theta$, but from Figure 3

$$\tan\theta = \frac{0.7}{2\times 3.7}$$

$$\therefore\ \theta \approx 5.4^0 \text{ and } \sin\theta = 0.094 = NA$$

$$\therefore\ f_w = \frac{1}{2\times NA} = \frac{1}{2\times 0.094} \approx 5.32$$ for the un-stopped lens (Figure 4)

For the lens with the added iris, the diagram applies (Figure 5)

$$\text{Now, } \tan\theta = \frac{0.4}{2\times 3.7}$$

$$\therefore\ \theta \approx 3.094^0 \text{ and } \sin\theta = 0.054 = NA$$

$$\therefore\ f_w = \frac{1}{2\times NA} = \frac{1}{2\times 0.054} \approx 9.26$$

for the stopped lens ($f_w/8$ was the target) (Figure 6).

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Figures 4 and 6 Microscope objective without (left) and with (right) additional iris.

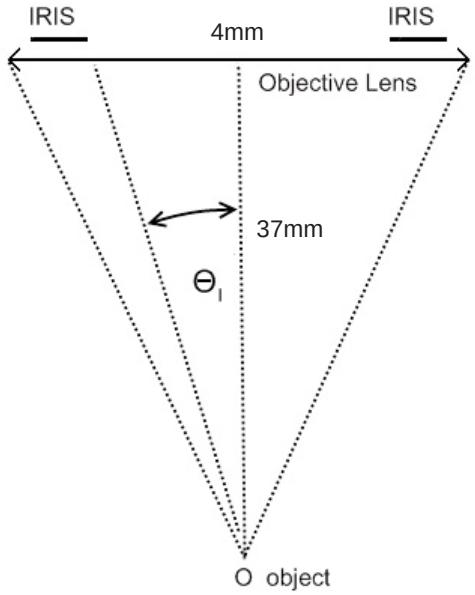

Figure 5 Diagram for calculating numerical aperture (NA): stopped objective.

Actually, the final calculation for f_w is not needed, as the depth of field (DOF) for the microscope objective

$$d = \lambda \frac{\sqrt{n^2 - NA^2}}{NA^2} \qquad (1)$$

where λ is the wavelength of light; note 500×10^{-9}m used as this best approximates to the source (Abramowitz and Davidson 2008).

For the lens without the iris added:

$$\therefore\ d = 500\times10^{-9}\ \frac{\sqrt{1-0.094^2}}{0.094^2} = 5.63\times10^{-5}\text{m} \Rightarrow d \approx 0.056\text{mm}$$

For the lens with the iris added:

$$\therefore\ d_i = 500\times10^{-9}\ \frac{\sqrt{1-0.054^2}}{0.054^2} = 1.712\times10^{-4}\text{m} \Rightarrow d \approx 0.17\text{mm}$$

(which is a three-fold improvement).

By simple geometry it can be shown that

$$NA = \frac{R}{\sqrt{R^2 + D^2}}$$

where R is half the iris diameter and D is the object lens distance (*see* Figure 5). By substituting for *NA* in equation (1) a graph of *f(d)* is plotted for varying *R*, where the DOF is shown to increase more rapidly as the iris reduces (Figure 7, *overleaf*). Based on the graph, the convenient iris diameter of 3mm, giving a predicted DOF of 0.3mm was assembled into the system. This procedure produced the photograph shown in Figure 9 *(see below)*, where the sides are now more distinct: f_w for this calculates as 12.34.

The outcome

Now, the gold flake had a thickness of *c.* 0.5mm and the uneven pitted surface extended down to something approaching 0.2mm. Hence the irregular surface is just about accommodated for by the improved depth of field (Figure 8). Note particularly the in-focus portions on the left hand side and the U-shaped pit to the right. The improved illumination towards the top is due solely to an additional high-intensity, but similar, light source positioned to one side (Figure 9). This was required to drive sufficient light through the modified system to produce a computer-viewable image.

The assumed clay minerals in the pits had their blue colour emphasised, probably owing to the incident light source: a 'white' LED whose blue component, generated by the GaN, peaks at just above 450nm and is much more intense than the cerium-doped yttrium aluminium garnet produced constituent, which peaks at *c.* 550nm and is centred at 580nm in the yellow part of the spectrum (Wikipedia 2008c). The colour can, however, be corrected with appropriate software adjustments.

Overall reproduction quality is restricted by the capability of the camera at 1.3M pixels.

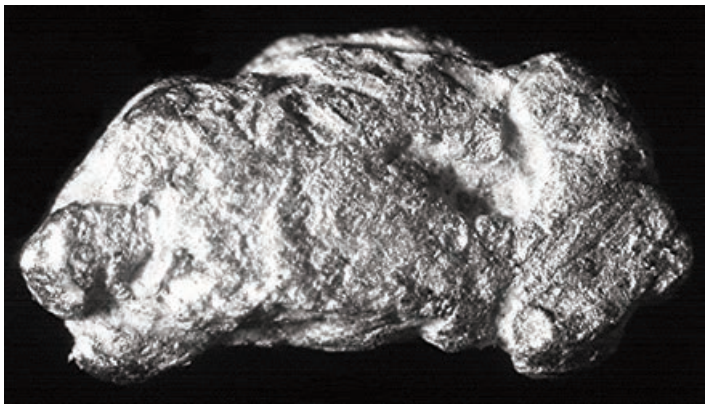

Figure 8 Gold flake under 4mm objective diameter (see discussion).

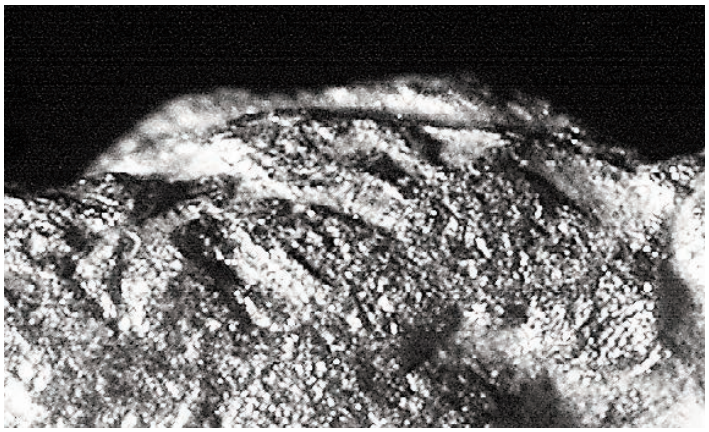

Figure 9 Upper edge of gold flake under 3mm objective diameter (see discussion).

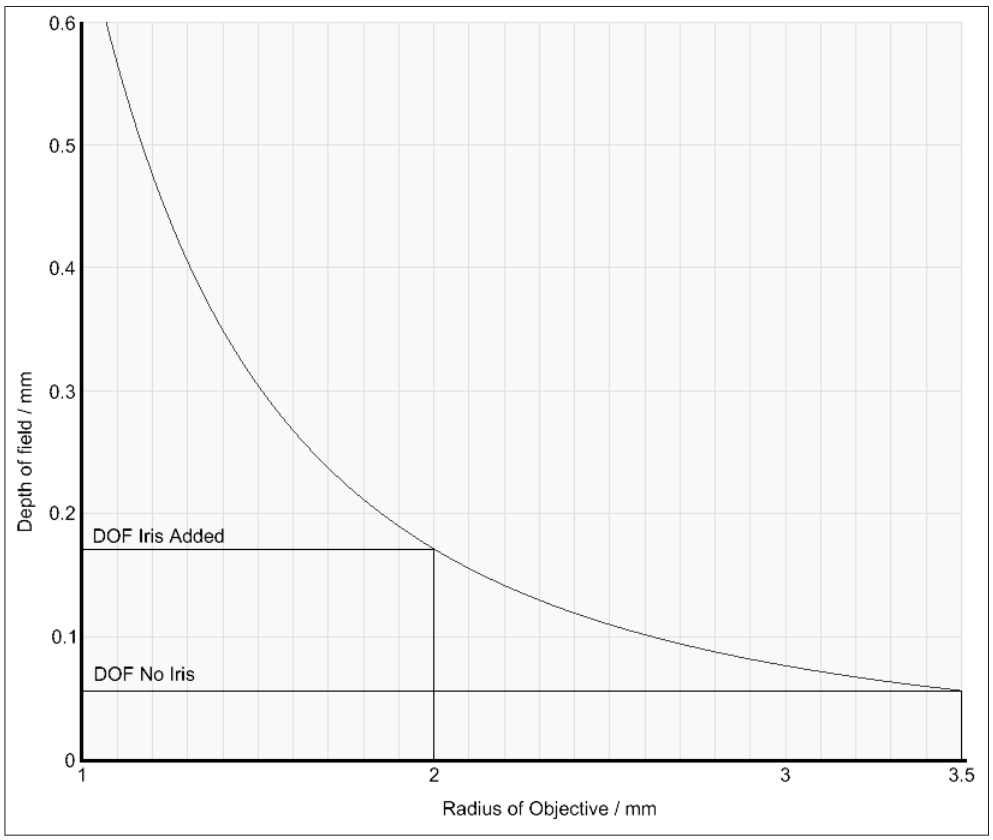

Figure 7 Computer-generated plot of objective radius against depth of field (DOF).

Discussion

The technique used has practical limitations dependent on the equipment parameters. The USB camera had a resolution of 1280px × 1024px on a charge-coupled device image sensor whose active surface measured 5.1mm × 4.1mm. These dimensions were calculated by indirect photographic means owing to the delicate nature of the electronics and a lack of published data to hand.

Two individual spots will coalesce and become indistinguishable through diffraction effects at a stage when their combined size ≈ $f\lambda$ (Wikipedia 2008d). Thus $f\lambda$ should remain greater than the length of a picture element; in this case 5.1mm/1280.

Hence at this moment $f\lambda = 5.1\text{mm}/1280$ giving an upper limit to f.

If, as before, λ is taken as 500nm we have the expression

$$f = \frac{5.1}{1280\times500\times10^{-6}} = 7.97$$

Or f/8

From this it is easy to calculate that this corresponds to an iris diameter of ~ 4.7mm. So a trade-off between resolution and depth of field begins at f/8 and in fact taking the photograph shown in Figure 9 was a little ambitious. To overcome this, a camera with greater picture element density could be used, or with film, a smaller grain size.

Furthermore equation (1) shows that DOF $d \propto \lambda$; hence, if pure red light is use, say 700nm, then d is increased by 7/5 or 1.4 by the longer wavelength.

Also for the resolving power R of a microscope, $R \propto \lambda$, but now R is required to be small. Hence, λ should be from the opposite blue end of the spectrum; but of course the views then become monochromatic.

Acknowledgements

The ideas described here were helped by discussions with Dr Steve Blake and Linda McArdell, MSc of the Open University.

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Stone on Stone

Of ancient lands... wind, echoes and shadows

Rob Heslop

Rambling alone in slow drizzle, I walked the length of Wasdale Head, scurried and scrambled to the summit of Scafell Pike, then meandered until I was lost. This is a green, rugged and harsh wilderness, where the undulating uplands are strewn with stone, boulders and big rock.

It was while negotiating this vast and lonely territory that the winds first began to gust. I looked at the ordnance survey, compass in hand; lost, maybe, but Glaramara can't be far. The winds now howled, and as the drizzle turned to rain, I first heard the sound.

Initially startled, I shrugged it off and ignored it. Time was getting on, and despite fatigue, I hurried. The winds intensified as at last I found a thin muddy track winding over stone and grass and muddy puddle alike; 'Glaramara, two miles this way', I said to myself.

Then I heard that sound again, louder this time. I stopped dead still and listened intently. 'Haunting gales whistling through valleys and over cliff and boulder', I reasoned, and pressed on.

But then I heard it yet again, just as a gusty vortex of wind ripped my plastic-covered map from my hand. It shot at speed and caught on a branching and twisted claw of heather. It flapped violently, before ripping. And all the while, that SOUND had remained.

Seemingly, the insistent presence of the sound was all around me; it came from neither left nor right, but from here, spot on where I stood.

I squelched in mud and puddle, bewildered, while turning to focus. Strangely ... and this is difficult to reason ... the sound diffused an air of tranquillity; or rather perhaps a kind of wisdom, or ancient knowing, or whatever; but it was not an eerie sound. I found a harmony with it ... then through that, felt the ambiance, or rather, an understanding, of our wild-land of so long-ago ... and of beautiful mysterious nature indeed.

For the sound was nothing but a fleeting solitary spirit from some-age-or-other. And this truly is, compared to our time, effectively a very ancient sound, as I came to realise that this supernatural effect had 'oozed' from the Neolithic period. (And yet how, seems of no importance). It just comes and goes ... and at first echoed as the hitting of stone on stone.

Neolithic people had carved and cut rock here in the manufacture of the stone axe; and their work endured day in day out, over generations, for centuries and millennia.

The stone-on-stone echo resounded so greatly that it somehow welded with the aggressive upland winds. The roughed-out hewn axes were carried from here to the lower valleys and dales, and were then worked further still by craftsmen to become the polished axe product.

They were then transported, and traded over great distances.

Many of those hundreds, if not thousands of ancient polished axe artefacts are found scattered today throughout the British Isles; and a large percentage of them have been directly provenanced to this extraordinary site — that of the Langdale Pikes of the Cumbrian Lake District National Park.

And to me, the detailed process of the petrological identification and provenancing of them initially also appeared as something of a mystery.

Early studies

Found in isolation or within archaeological contexts, the discarded prehistoric stone axes from across Britain and Ireland were gradually collected. Pioneering work for provenancing the fine- to coarse-grained lithics was started during the 1930s by A. Keiller, H. H. Thomas and S. Piggott, among others, for the Dorchester museum. Together they developed the Implement Petrological Committee (IPC), being sponsored by the Council for British Archaeology (CBA).

Colour, texture and grain size of macroscopic lithic provenancing is vague. Microscopic petrology is therefore the indispensable analytical tool, often ultimately 'fingerprinting' the characteristic identity of the artefacts to raw material. Through progressive organisation, divisional IPCs characterised and catalogued these ancient tools. The results were then compared, record cards compiled and definite statistical patterns began to emerge.

Sourcing the stone

By the early 1950s, several hundred stone artefacts had been successfully identified and sourced, and individual petrological groups were being recognised. Comparing various IPC databases and correlating these to data of suspected on-site raw material may thus lead to inclusion within a recognised group for newly examined specimens with at least near matching affinities. Today, 34 major groups are now numbered with Roman numerals, and correspond to the geographical location of their axe 'factories' (quarry) sites. Examples thus include not only the Great Langdale group VI area, but also, for example, group VII of Graig Lwyd, north Wales, group XXX in northern Scotland and group IX from Tievebulliagh, in northern Ireland.

Sub-groupings are frequently needed, however, as petrologically wide-ranging stratigraphies naturally show degrees of variability. Ultimately, stone axe study reports describe petrological provenance sites, axe typologies, archaeological associations, maps and statistics; and yet certain artefacts simply remain un-sourced.

To characterise an implement, a section is cut by using a small wire saw, the thin section is then cleaned, polished and prepared for observation under the petrological microscope. (This process, however, effectively damages the artefact and consequently it needs to be repaired).

Transmitted polarised light is reflected from the tiny translucent mineral components within the thin slice (X-ray diffraction). These data are collected by an analyser, enabling a mineralogical identification to be made of that stone, especially when primary mineral assemblages are largely present. For example, epidote is found within Group VI of the Great Langdale Pikes rock.

Trace elements are detected by using a second complementary technique — X-ray fluorescence spectrometry (XRF) — whereby the smooth, cleaned, thin outer surface of the artefact (thus non-destructive) is examined. Several identical tests are taken from the same specimen, and characterisation is established on the basis of a mean average statistic. The various trace element percentage contents, such as thorium, rubidium or strontium are recorded.

Thus, a combination of several methods 'fingerprints' the stone.

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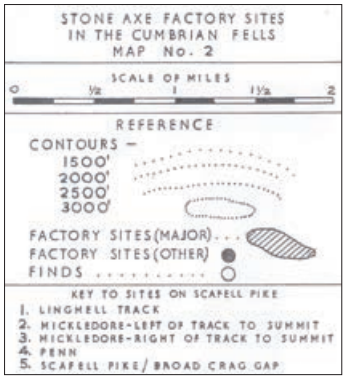
Stone axe quarries

In 2001 Ixer and his colleagues (Ixer *et al.* 2002) adopted this technique while correlating 12 axes found in the English Midlands, of which four were from the Group VI Great Langdale area. Stone axe study statistics include a 30% total of all petrologically classified implements as being provenanced to Group VI, showing them as the most numerous stone axe artefacts found in Britain and Ireland. This scientific provenancing sequence has demonstrated that the Langdale implements travelled far, sometimes in excess of 500km.

Basically the Langdale Pikes are formed of volcanic tuff, a fine-grained petrified ash deriving from the Ordovician period, of the lower Palaeozoic Era. Together the Langdale Pikes and Scafell fells groups form part of the Borrowdale Volcanic Series. This series, however, does not have a regular mineralogical or chemical composition throughout; and varies with andesite, rhyolite and hornblendite. In 1993 Richard Bradley and Mark Edmonds argued in 'Interpreting the Axe Trade' that sub-grouping therefore may be required for the wide-ranging Borrowdale tuffs. Therefore, other lesser petrological groups are also known from Lakeland, such as groups XI and XXXIV.



At source, the archaeological significance of the axe 'factories' within the Central Lakeland Fells were first truly recognised by Watson (in Clough and Cummins 1988), who recorded grey-green axe 'rough-outs' and waste chippings, at Stake Pass between Pike o' Stickle and Thunacar Knott in the Langdale Pikes area.

Over several years many flakes and discarded axe rough-outs were gathered, and the examination of their petrology's by Wallis, since 1959, was included in the excellent CBA Research Report, Stone Axe Studies (Clough and Cummins (eds) 1979 and 1988). Earlier works by Bunch and Fell (1949) and by Plint (1962), greatly expanded the geographical limits of the prehistoric factories, and they identified the various screes of the Pike of Stickle as the main source of the raw material. Most were catalogued as Group VI axes, or 'near' to Group VI (Figure 1).

Scafell Pike, Lingmell Ghyll, Glaramara, Thunacar Knott, Stake Beck and Harrison Stickle have all since been added, as secluded sites where waste from knapping has also been found.

Several methods of quarry work have been noted in the Great Langdale uplands, including the site in Figure 2 *(opposite)*, where rock was cut through natural fissures at the base of the cliff face. In some areas, following this technique, 1.5m thickness of waste rough-out flake debris (débitage) piled around the area of exploitation. According to Edmonds (2004), in some areas, certain outcrops were even apparently burnt and heated before the rock was friable enough to be smashed for rock extraction.

In all, 35 grouped sites are known from the Langdales landscape, comprising a total of nearly 600 recognised, individual quarry/knapping sites.

Stone axe manufacture

Basically, two types of rough-out axe models are found here, both in varying degrees of unfinished manufacture: narrow butted axes, and wider butted axes. Varying in size, both models tend to be long and oval shaped. These seemingly damaged, or broken rough-out implements were rejects that were initially

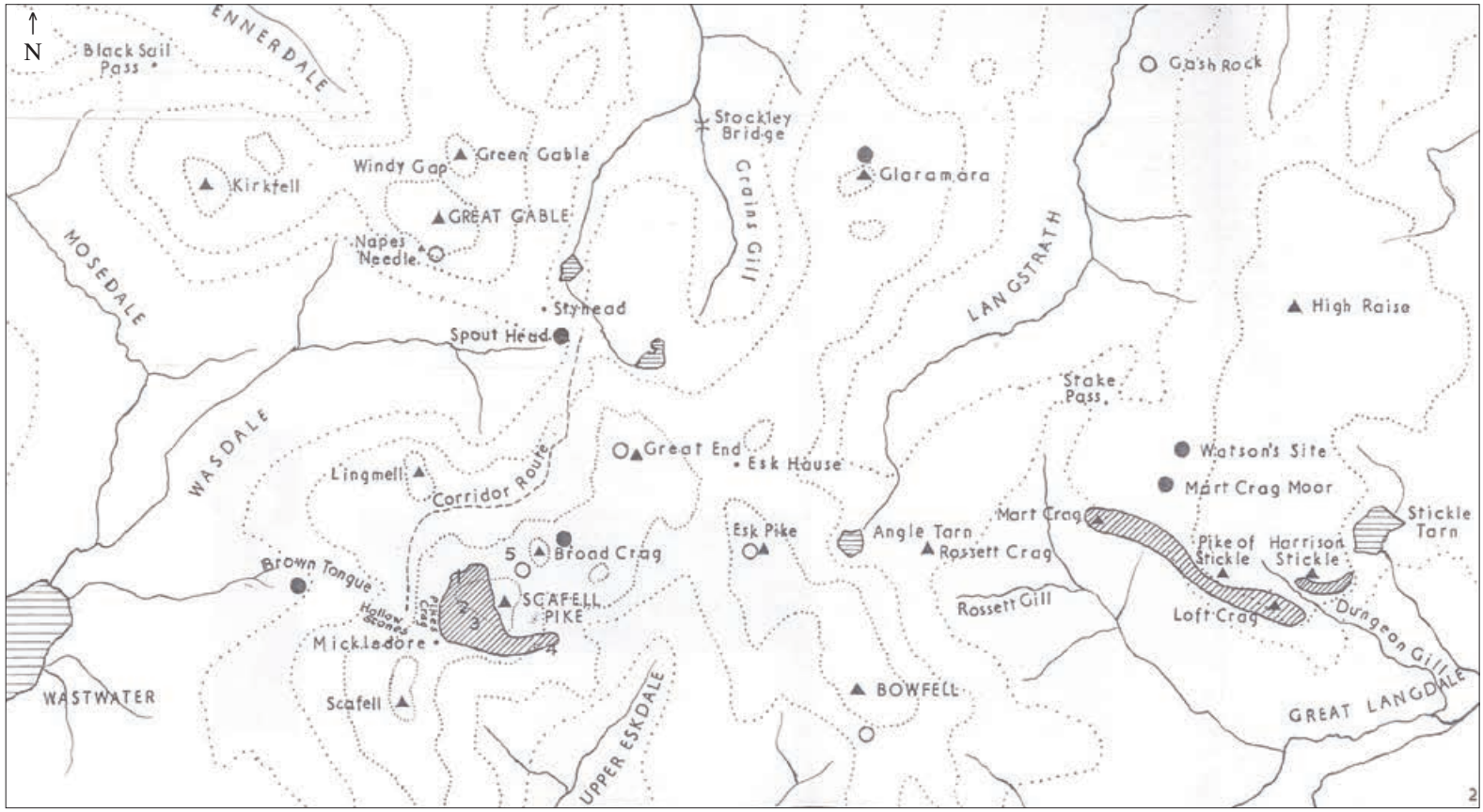


Figure 1 Map of ancient quarry area ('factory site'), showing Scafell Pike, Wastwater lake (bottom left), and several dales of the Lake District (drawn by W. G. Stevens, in Plint 1962; by kind permission of Audrey Plint).

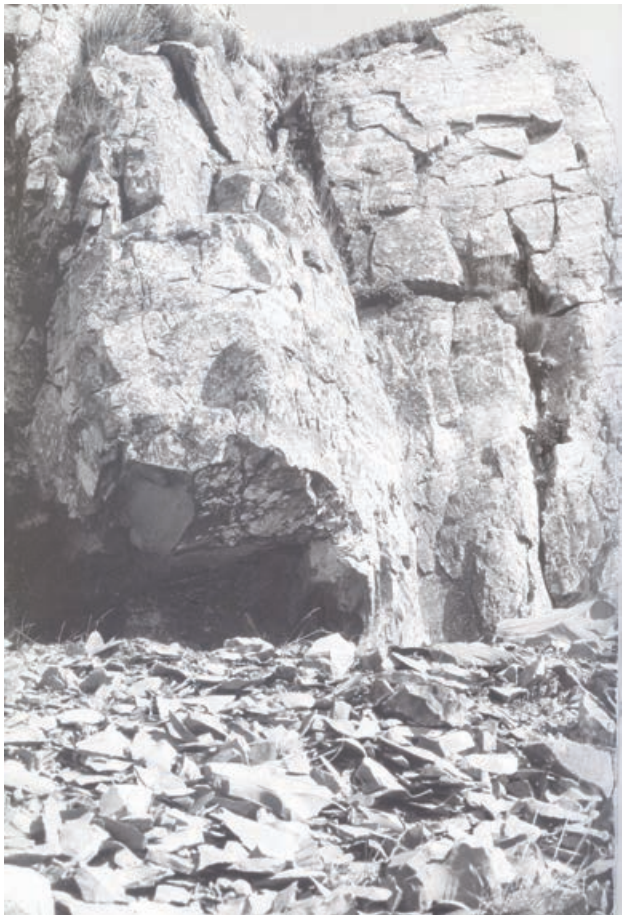


Figure 2 Stone axe quarry sites have been identified through cliff scars and/or débitage scatter, as seen at this site in the Langdales (by kind permission of Mark Edmonds).

intended for full manufacture; one abandoned rough-out was recently discovered under moss and perched on a small, lofty ledge (Figure 3).

Other remnants at this huge archaeological vestige are the isolated granite rocks, apparently transported by the axe makers from the west, at Ennerdale (according to provenancing) and the Vale of Eden (where palaeoenvironmental evidence suggests woodland clearance from *c.* 3500 BC); the granite rocks were found among the prehistoric waste rubble and flake piles, present among the peaks of Great Langdale area.[1]

These rocks are thought to have been used as anvils, and hammerstones for pecking and knapping axe rough-outs at the quarry sites; before taking the axes from the fells for more refined work into grounded and polished axes. Once refined and polished, they would have been hafted and tied onto wooden shafts.

Stone axe trade

Archaeological evidence indicates that extraction of stone from this upland landscape began perhaps *c.* 4000 BC — or even earlier during the late Mesolithic period — and endured well into the early Bronze Age, thus a span (perhaps) of several thousand years. Finds from these times include a group of Langdale rough-out axes from Pilling Moss, discovered below the peat level; their context corresponds to small-scale forest clearing dating to the early Neolithic, as seen through palaeoenvironmental analysis from Barnfield Tarn and Thunacar Knott, and from English and Irish Sea coastal sites at Bidstone Moss, Flea Moss Wood and Ehenside Tarn. Forgotten axe hoards have even been found grouped in hideaways of rocky gaps, such as the find at Skelmore Heads, Ulverston.

Excavation at Ehenside Tarn in 1869 recovered wooden Neolithic artefacts, rough-outs and polished axes; and even sandstone 'polissoirs' — grinders for refining and polishing the rough-out implement, for simple roughed-out axes would have been inefficient as a true cutting tool, as they would catch and 'jam' in live, sap-filled trunks (Figure 4, *overleaf*).

One polished axe at Ehenside Tarn was incredibly still held within its beechwood (*Fagus sylvatica*) haft. Ongoing palynological research at the tarn has dated these activities to between 3900 and 1500 calibrated BC. The lithic implements were provenanced to Group VI of the nearby Great Langdales. Petrology thus demonstrates the transport from the Langdales to Ehenside Tarn.

I scoured detailed maps of the region attempting to identify an ancient route from upland to tarn, a most elusive task indeed! How were they carried? Were they carried in skin bags perhaps, or in some kind of cart? Or were they simply carried individually, after an occasional trip over the peaks?

Finished implements from the Lake District may have been intended for exchange across the sea to the Isle of Man, along the Solway Firth, south along the west coast, or even farther to Ireland, where Group VI polished axes have indeed also been recovered; and in return, several Irish lithics have been found in Lakeland.

Several early stone circles, dating from the Middle Neolithic of *c.* 3370 BC, are scattered through Lakeland: Castlerigg, Swinside, Long Meg and Brats Hill for example (Wilkinson 2005). Investigations at these sites have revealed deliberately buried polished axes originating from the Langdale outcrops, suggesting another link to the traders, if not buried by the traders

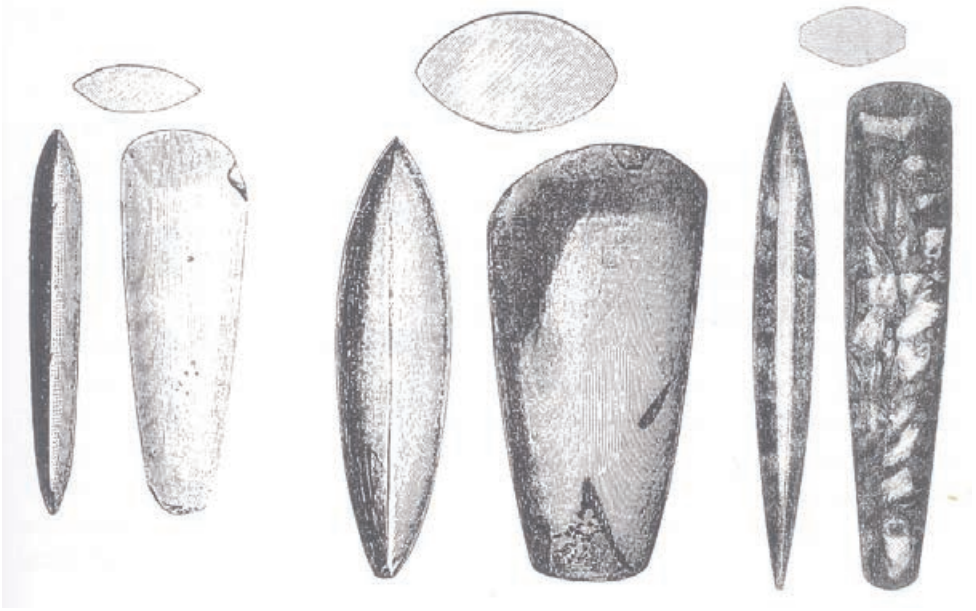


Figure 3 Various Langdale axes: left and centre, polished and completed implements; right, an incomplete rough-out model (approx. ¼ size) (after Darbishire; with kind permission of Mark Edmonds).

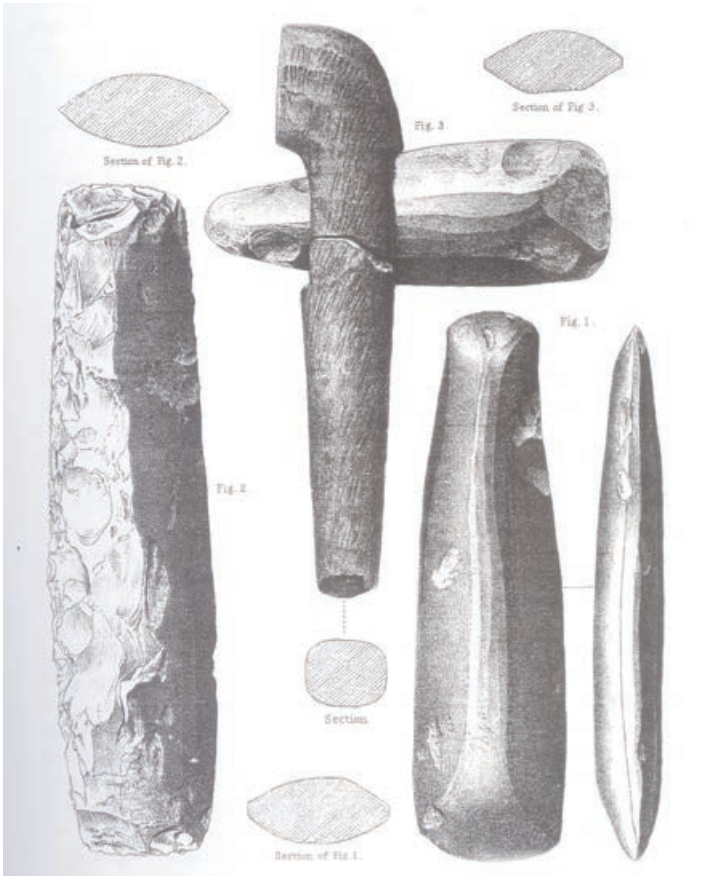


Figure 4 Part of the Ehenside Tarn trove: left, a rough-out axe; right, a finished polished specimen; centre, the complete hafted tool, illustrated as found (approx. ¼ size; drawn in 1873; from Edmonds 2004, by kind permission of Mark Edmonds).

themselves. Other Neolithic circles are known at Ballynoe in Ireland and Lochmaben in Dumfries — both areas within sea-trading reach of the Cumbrian coast, and thus also suggesting potential ancient connections. Ongoing excavation and study at Billown, Isle of Man (the Neolithic Billown Project) may also prove to correlate with sea-faring links of the Group VI axe-making peoples, for their implements have been recovered at the site (Darvill 2005).

Implements from the Langdales were transported, exchanged and bartered most probably with neighbouring settlements, whose inhabitants, we can speculate, might have in turn transported axes for barter with more distant settlements. Theoretically, the farther they spread, the more valuable they would have become, and over time they effectively diffused throughout Britain and Ireland (with the greatest concentrations of them being recovered from eastern England).

Greatly favoured for their durability and natural ability to shine, the polished axes were treasured, and may have been objects of social importance. And effectively, enigmatic, special rituals might once have surrounded the polished axes, as shown by bizarre water-related finds, such as that at Portinscale, near Keswick, where several axes were discovered hidden under an ancient tree stump, in what was once a bog. Other examples have been dredged from wetland sites, found deposited (or thrown) into tarns, and even dredged from the Thames.

It is most possible that other Neolithic (and early Bronze Age) stone axe work-sites and isolated artefacts will be discovered in Lakeland. Increasingly sophisticated techniques of archaeological geophysical survey along the spreading long valleys near the Central Fells and coastal regions may locate remnants of small prehistoric settlements, polishing areas and waste flake sites remaining under thin soil cover.

These valleys and flatlands would surely have been partially de-forested, and consequently may have been the harbours of the early artisans — the trades-people of the precious stone axe. Once thriving for maybe several millennia, the early peoples shaped the land, clearing the wildwood with the swing of the axe as an evolutionary step for more space, as agricultural practices and animal husbandry spread (Figure 5).

Trading trails stretched through necessity and want, and together through common ritual and beliefs, the henge monuments became a fabric of fashion, of which some of the very earliest examples in Britain are found in Cumbria.

Conclusion

Weaving within these life-lines was perhaps a common language for trade, bringing with it a common identity; thus through the wide-spread common value of trade monopoly, came a profound harmonising of social exchange, which prehistorian Caroline Malone named the 'Neolithic achievement'.

Only through the scientific certitude of petrological identification[2] from artefact find-site, toward the original quarry source of these once long-slumbering stone implements can wide-spread geographical links be defiantly inferred. We therefore have here, perhaps not the echo-in-the-hills of stone on stone, but a clear surviving prehistoric shadow moving upon our ancient land.

[1] These granite rocks, which seem to have been used as anvils, are provenanced to the western Lakeland valleys, demonstrating prehistoric connections between these areas. I would have liked to have found more complete descriptions of these anvils, as their sizes and weights might suggest how they were transported. They might simply have been carried by hand. The carrying of such

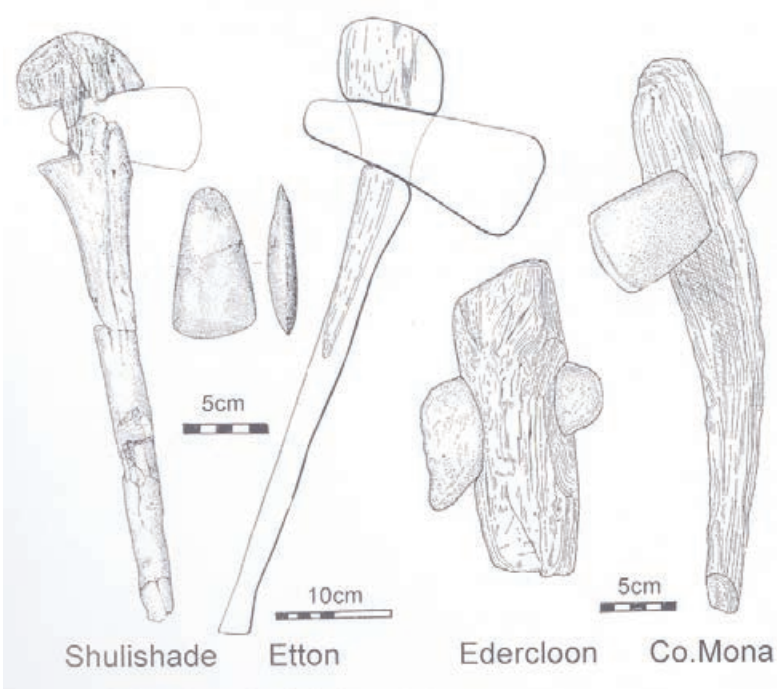


Figure 5 More complete hafted Neolithic axes from around Britain. Hawthorn, beech, apple, alder, oak, birch and pine were used for hafting (no scale; after Malone, Pryor, Sheridan et al. *in Malone 2001; by kind permission of Caroline Malone).*

heavy rocks up, may indicate that similarly heavy loads were carried down, rather than just occasional handfuls of axe rough-outs, thus showing that the Langdales were a true 'factory' site.

[2] The petrological identification of flint artefacts is a different process to that of lithic specimens. Neolithic flint axes were frequently extracted from underground mines, and not from the surface or mountain top, as with classic stone axes. Prehistoric causewayed enclosure campsites have, on occasion, been excavated within the near vicinity of the ancient mines, and frequently reveal flint-knapping scatter, and again, polissoirs (Pryor 2003).

The most famous British flint mines, Grimes Graves in East Anglia, date to *c.* 3000 BC. Up to 360 individual shafts were sunk for flint extraction at Grimes Graves, during a wide-ranging span of activity lasting perhaps 1,500 years. Earlier mines are also known at Blackpatch and Cissbury for example, dating to 4000 BC. Flint mines have also been recognised in north-eastern Scotland, as well as in Ireland, where open-cast flint mines have been identified.

The author would like to remind readers that it is irresponsible and counter to research methods to collect archaeological specimens at random in the field. Please, do not collect artefacts from the Langdales.

Acknowledgements

Many thanks to Mark Edmonds, Caroline Malone for their permissions to use illustrations from their books, to Audrey Plint for her permission to use W. G. Stevens's map in R. G. Plint's article, and to David M. Jones for his encouragement.

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Book Review

H. Lewis and G. D. Couples (eds) 2007 *The Relationship between Damage and Localisation*. Special Publication 289. London: The Geological Society (ISBN 978-1-86239-236-6; 247pp; £80)

Collectively, the papers in this Geological Society Special Publication provide an intriguing exploration of the evolution of geomaterials and the structures and fabrics — the manifestations of damage and localisation that we encounter in the field and laboratory.

Compiled following a series of Euroconferences on rock mechanics and rock physics, the volume brings together current research from the field, experimental work and modelling.

Twelve independently refereed papers examine the subject from the diverse perspectives of structural geology, seismology, reservoir engineering and others, and cover a variety of geomaterials, principally sedimentary rocks. A useful introduction explains the authors' differing interpretations of the terms 'damage' and 'localisation', summarising some key findings and identifying common themes emerging from the research. The many figures and photographic images are reproduced to a very high standard.

Damage and localisation are examined from a range of scales of observation, from grain-scale structures induced in the laboratory, to crustal-scale features, such as the heterogeneous fault rocks encountered along Japan's largest strike-slip fault, known as the Median Tectonic Line (MTL).

Topics explored include how different geomaterials, and hence their physical properties, evolve during deformation, sometimes in an unpredictable, non-linear fashion; how factors such as lithology, grain size, porosity, thermal gradient and earlier phases of deformation affect localisation; how faults that form barriers to fluid flow may become conduits at greater depth; and how seismic reflection data can be used with greater confidence to predict permeabilities.

Some hitherto accepted concepts are challenged. For example, faults have long been regarded as a response to static stress regimes, but are they in fact a cause of stress rather than a consequence?

The precise mechanisms by which geomaterials deform and the changes resulting from that deformation are pertinent to many disciplines, including engineering, hydrogeology, waste disposal, hydrocarbon recovery, underground storage and seismology.

Although not an easy read, this Special Publication is certainly a thought-provoking one, and some of the work presented here may ultimately change the way we understand deformation and its practical consequences in the future. It is suitable for advanced undergraduate or post-graduate study, and will be of particular interest to readers engaged in modelling damage and localisation in geomaterials.

— Caroline Peters BSc (Hons) Geoscience (Open)

The rise and fall of late Triassic sea level and its interaction with basinal brines

Kate Evans

Introduction

The late Triassic sediments found in South West England and the South Welsh Coast comprise a series of basal sandstones and breccias (e.g. the Sherwood Sandstone), the Mercia Mudstone Group (MMG) and the Tea Green and Grey Marls of the Blue Anchor Formation (BAF), and the Westbury and Lilstock Members of the Penarth Group (Figure 1, *opposite*). These rocks were deposited in the Wessex, Worcester and Somerset basins during the late Triassic (Woodcock and Strachan (eds) 2006). The base of this succession is unconformable on folded Palaeozoic strata (predominantly Tournaisian Limestone) (Green 1992) and is clearly diachronous (Figure 2). The MMG and overlying fully marine strata of the Penarth Group represents two pulses of marine transgression. The first represents the transition from the sub-aerially exposed Carboniferous Limestone to intermittent connection to the Tethys Ocean (Benton *et al.* 2002), which resulted in the deposition of the Sherwood Sandstone, the MMG and BAF. The second was caused by the Rhaetian Sea transgression and resulted in deposition of the Penarth Group (Benton *et al.* 2002).

The following short guide attempts to illustrate the environmental interpretation and sequence stratigraphic significance of these rocks through five different outcrops. Visits to each site will show the full sequence of the transgressions.

Note: It is not feasible to visit all localities in one day.

Abbreviations used in the text:
TST = transgressive system tract; TS = transgressive surface; HST = highstand system tract; MFS = maximum flooding surface; SB = sequence boundary.

Palaeogeography, climate and sea level

During the Triassic, Britain was part of the super-continent Pangea and lay approximately 30° to 40° N (Green 1992). The equatorial climate in this region appears to have been a mid- to low-latitude, continuously dry belt evident by the common red-beds and frequent evaporite deposits (Woodcock and Strachan (eds) 2006). Other geological events in the late Triassic to Jurassic periods were flood basalt events (Benton *et al.* 2002) caused by continental breakup, the rifting of the Atlantic and three mass extinctions (Benton *et al.* 2002; Brenchely and Rawson (eds) 2006).

Basin formation and initial sediment supply

The Wessex, Somerset and Worcester basins formed in the Permian during the breakup of Pangea that activated rift basins and syn-sedimentary faults. These continued to be active throughout the deposition of the late Triassic sediments (Woodcock and Strachan (eds) 2006). The newly formed fault scarps to the north and south of the basins and local highs to the north west (*see* Figure 2) supplied sediments during the mid- to late Triassic (Anisian / Scythian stage) (Woodcock and Strachan (eds) 2006). Here, coarse-grained clastics and breccias were deposited by rivers, braid plains and alluvial fans (Brenchely and Rawson (eds) 2006) formed in what has been interpreted as a marginal lacustrine environment (Brenchely and Rawson (eds) 2006; Green 1992). These rocks overlie the early Carboniferous strata.

Ladram Bay and along the Avon in Bristol city centre show examples of terrestrial Anisian age sediments.

At Ladram Bay red ferrous sandstone with graded beds, erosive pebble lags and large-scale trough cross stratification (TCS) are exposed. Also present are ripped-up beds of alluvial

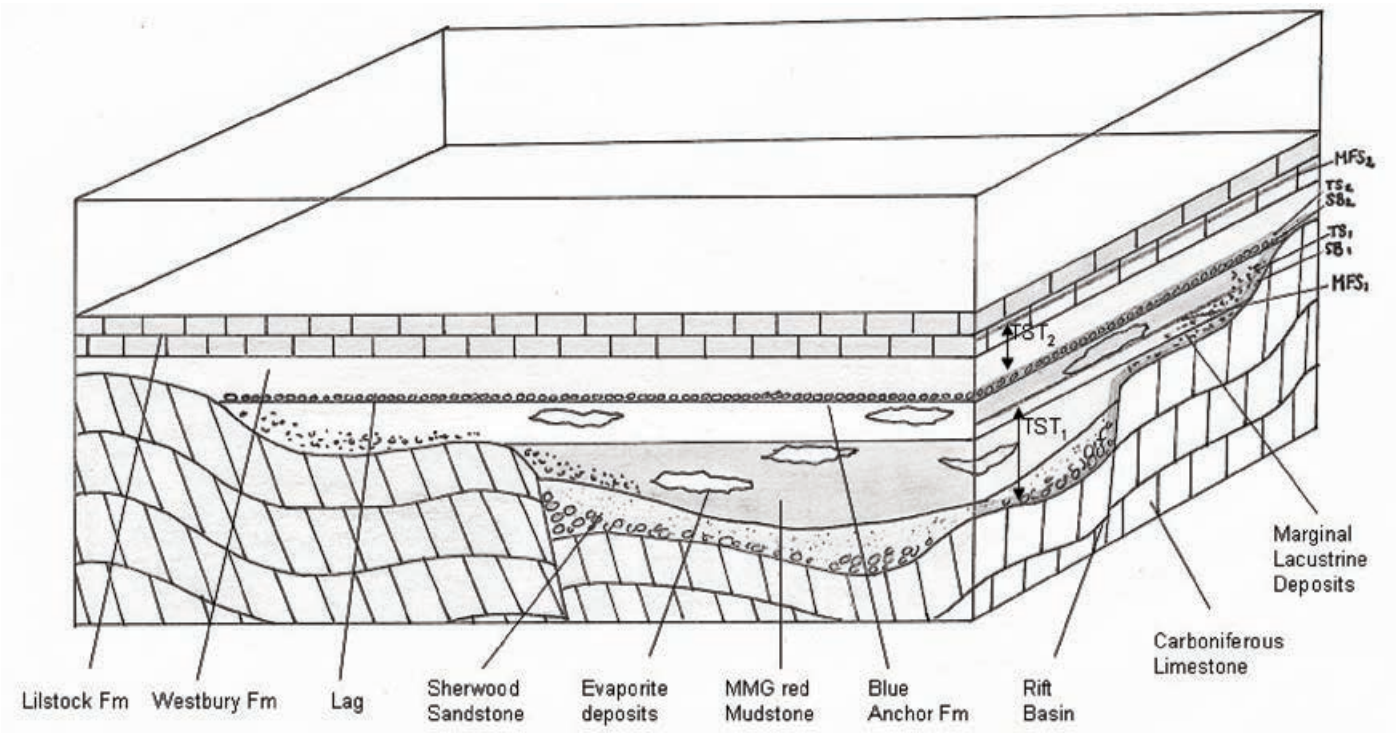

Figure 2 Schematic representation of the evolution of the late Triassic lithology in South West England and South Wales.

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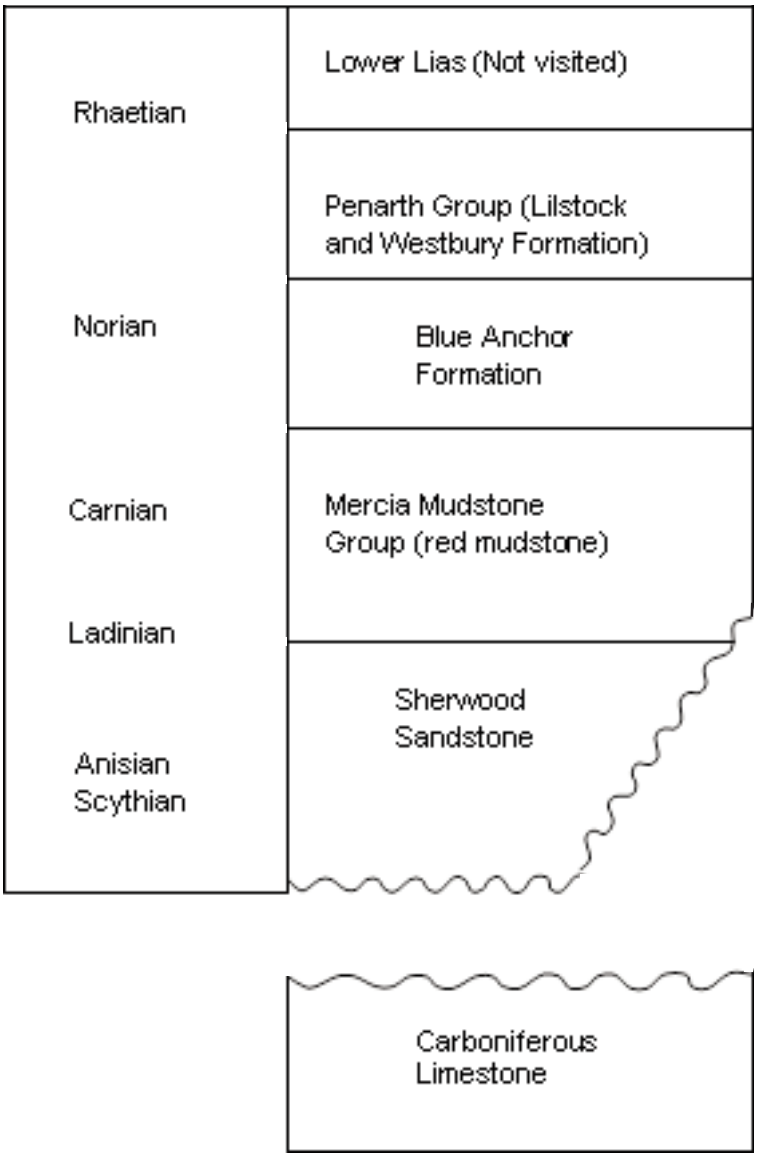

Figure 1 Statigraphic column for the late Triassic strata in the study area.

mudstone (Figure 3). These features indicate high-energy alluvial environments and are attributed to braided streams (Benton *et al.* 2002). Higher up the cliff, the sedimentation changes to planar cross stratification that is cross cut by rhizoliths. Both features suggest the transition to a calmer alluvial environment. Above these rocks, the general lithology changes to a heterolithic facies of sand and shales, indicating a further decrease in energy. This final environmental change corresponds to an initial transgression into the lacustrine/sabkha environments of the Mercia Mudstone Group.

Evidence for sea level change and changing environment

Westbury Garden Cliff, Gloucestershire (Figure 4)

The main lithographic units preserved at this outcrop include the MMG (capped by the Blue Anchor Formation) and the base of the Penarth Group (comprising the Lilstock and Westbury Formation). The red mudstones of the MMG are a red, fine-grained, argillaceous, dolomitic mudstone and siltstone with concoidal fractures (Green 1992). Also present are frequent patches, streaks and bands of grey-green shale, the cause for which it has been suggested is differing oxidation states of the iron in the rock

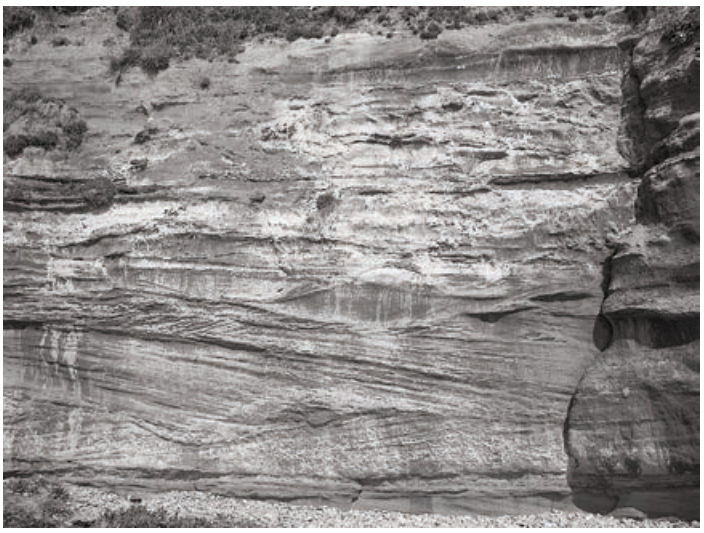

Figure 3 Ladram Bay (Showing TCS).

(Green 1992). The Blue Anchor Formation consists of green to grey argillaceous mudstones. The initial, highly oxidised sediments of the MMG suggest arid depositional environments in a playa lake that was periodically connected to a shallow marine seaway or a hypersaline coastal sabkha (Green 1992). The transition from red to grey-green shale in the Blue Anchor Formation has been attributed to increasingly more humid conditions (Woodcock and Strachan (eds) 2006; Green 1992) (i.e. less oxidising and a rise in lake levels).

Above this transition is a sharp, erosive conglomerate sandstone. This sandstone features cross bedding and bioturbation (by a relative of the horseshoe crab). Also present is a well defined lag of phosphatised (Benton *et al.* 2002) bone, fish debris and coprolites. These rocks contain pyrite and chalcopyrite cement. Immediately above these sands there is a transition to darker, organic-rich shales and then to the limestones of the Lilstock Formation, which is dominated by bivalves.

Sequence stratigraphic interpretation

The increase in the reduction of iron preserved in the transition from the MMG to BAF is interpreted to represent a TST (TST_1) (*see* Figure 2). However, no MFS is preserved here, possibly owing to erosion of the HST by the overlying conglomerate. The erosive base of the Penarth Group is the best candidate for a

Figure 4 Westbury Garden Cliff.

sequence boundary (SB_2), which is overlain by a marine, phosphatised transgressive lag. The transition from the black shales to the open marine limestone is further evidence of the transgression (TST_2). An MFS (MFS_2) (*see* Figure 2), although not easily recognisable, is likely to be in the limestone. The reduced thickness of TST_2 suggests that there was a significant reduction in accommodation space during the Rhaetian Stage.

Barry Island, Vale of Glamorgan (Figure 5)
At this location the basal conglomerates of the MMG can be seen above the unconformity with the Carboniferous Limestone. This conglomerate contains clasts of Carboniferous rocks and has an irregular notch-like form comparable to raised beaches and wave cut platforms (Brenchely and Rawson (eds) 2006). It is suggested that these are the marginal lacustrine deposits of the playa lake (Brenchely and Rawson (eds) 2006). The conglomerate is overlain by a very thin layer of the MMG and an erosive-based green sandstone that grades upward through to shales with nodular evaporites to inter-bedded limestones from the Lilstock formation. The sequence of shales thins toward the highs of the Carboniferous Limestone.

Sequence stratigraphic interpretation
The unconformity between the breccias and Tournaisian Limestone represents the first sequence boundary (SB_1). This locality also shows progressive onlap of an uplifted Palaeozoic topography. The breccia at this location can be interpreted as the transgressive system of lacustrine/beach deposits. Like Westbury Garden Cliff, a prominent sequence boundary (SB_2) occurs above the shales of the MMG. This is overlain by a TST through to the Limestone of the Lilstock, where a possible MFS is located.

Figure 5 Barry Island (Carboniferous in foreground).

Evaporite Features

Aust Cliff, Avon (Figure 6)
This site shows a very thick exposure of the MMG and BAF and also good exposures of the Westbury Formation and Penarth Group. Fractures, both parallel and conjugate to the bedding, are a significant feature of this outcrop and have enabled basinal brines to migrate up through the MMG forming frequent evaporite nodules. However, these evaporites do not migrate as far as the BAF. The evaporites present are gypsum and anhydrite (Green 1992).

The sequence stratigraphical interpretation of the section compares to that at Westbury Garden Cliff. However, the presence of evaporites in the MMG suggests that some late Triassic tectonic events occurred in this area to cause the migration of basinal brines up through the sediments of the mud flat/sabkha setting.

Figure 6 Aust Cliff.

Watchet (Figure 7)
At this locality a prominent extensional fault downthrows the rocks of the BAF against the MMG. This fault was periodically active during deposition and as a result the evaporites are inter-bedded throughout these rocks in greater amounts. They are predominantly preserved in the deposits of the BAF. The evaporites occur in two different forms: primary deposits that are parallel to the bedding and secondary deposits that fill cross-cutting veins and fractures (the latter possibly caused by tectonic events).

The existence of more extensive evaporites in the BAF than MMG implies a more prolonged period of exhalation of basinal brines and is also consistent with this location being in close proximity to a major syn-sedimentary fault.

Conclusion

In summary, a comparison of several localities with outcropping late Triassic rocks provides an insight into the dynamic evolution of environments that occurred in Southern Britain during this

Figure 7 Watchet (showing extensional fault).

period. Climatically, this period changed from arid, desert-like conditions to an increasingly humid environment. Sedimentologically, these deposits reveal a progressive transgression over undulating, eroded Palaeozoic rocks. This transgression was pulsed and enabled the exhalation of salt-rich basinal brines onto a rifting lake/sea floor. Later rises in sea level transgressed unchecked over the lake sediments to form the fully marine conditions characteristic of the Rhaetian Stage.

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The author

Kate Evans has been an OUGS member for two years and lives in Oxfordshire. She is currently studying for an OU BSc (Hons) in Geosciences and is due to finish in October 2008. This article is a report on a project she did, associated with S369 Sedimentary Record of Sea Level Change, on the late Triassic sediments in Southern England. Kate formerly worked in the agricultural industry and is now seeking to change her career through her OU studies.

Book review

Gordon L. Herries Davies 2007 *Whatever is Under the Earth – The Geological Society of London 1807 to 2007*. London: The Geological Society (ISBN 978 1 86239 214 4; hardback, 356pp; £25)

This bicentenary history of "the oldest national geological society in the world and the largest in Europe" is really great fun. You can tell it is going to be from the chapter headings: 'The Creation 1807'; 'Primordial Life 1808–1825'; 'The Volcano Erupts 1825–1844'; 'The Dinosaurs 1844–1875' (dinosaurs in the sense of those who "internationally … dominated the geological scene just as once the real dinosaurs had held sway over the Mesozoic world" — Buckland, De La Beche, Murchison, Sedgwick, Darwin and Lyell); 'Placid Sedimentation 1875–1907'; 'The Centenary Lode Autumn 1907'; 'Seismic Convulsions 1908–1924'; 'An Endangered Species 1925–1963' (when the Society increasingly "had lost its way … was stuck in a rut"); 'Thrusting and Overturning 1964–2005'; and 'The Society upon a Plate'.

The sparky extended metaphors pour out, page after page, enlivening what could so easily be a worthy but heavy tome. Professor Davies, who has already written the sesquicentennial history of the Geological Society of Ireland, has thoroughly enjoyed writing this affectionate but acute tale of the successes and failures of the Geological Society over 200 years, and he passes his enjoyment on to the reader. It is an extremely personal account. The end, when he sits in the empty Council Room, musing on George Greenough, John Joly and Archibald Geikie, on the agreement of 2005 (which has assured to the Learned Societies occupancy of Burlington House for the foreseeable future), and on Burke's aphorism that "You can never plan the future by the past" ("Lyell might not wholly have approved of such a dictum"), has something of the poignancy of the end of Primo Levi's (1984) book *The Periodic Table* — when the carbon atom, which had spent hundreds of millions of years locked up in limestone and then passed round the world as CO2, been in a vine, a wine, a liver, a cedar, an insect and a glass of milk, ends up in the nerve cell that enables the author to make his final full stop.

Davies' achievement can be seen by comparing his work with the bicentenary history of the Royal Horticultural Society, founded three years earlier by very similar people. That handsome volume weighs in at about three and a half times heavier, needed over a thousand subscribers, and has more coloured plates. But it needs two columns to each page and while useful to dip into for the achievements, say, of the great reforming president Sir Trevor Lawrence, or the RHS's involvement in 'Floral Arts', is not exactly readable. I defy anyone who opens the GeolSoc history not to be hooked by this tale of geologists politicking, cooperating, leading the world or falling behind it, coping with wars and windfalls, and reflecting British society and its tumultuous changes. I hope that it is often borrowed from the library of our humbler society — especially as it comes with a wise preface by the most beguiling geological populariser of our day, Richard Fortey, bicentennial President.

— Philip Clark MA BSc

Langkasuka — ‘the land of all one’s wishes’

Carol Hagan

Introduction

Langkasuka is better known as Langkawi, an archipelago of 99 islands located about 30km of the west coast of peninsula Malaysia, with Pulau Langkawi being the largest island in the group. This is where I returned after a gap of 15 years for a short break and for a good opportunity to get face to face with Asian rocks.

Apart from airport concourses and hotel lobbies, this was my first foray into anything geological in its natural state in almost two years. To say my knowledge was rusty and that I needed to get my eye in was an understatement!

Langkawi was designated Malaysia's first (and so far only) Geopark in May 2006. Delegates from UNESCO visited there at the end of March 2007 to decide if the park could be added to their Network of Global Geoparks. They are expected to reach their decision in June 2007.* In Langkawi, you can visit the oldest rocks in Malaysia, a million-year-old rain forest, sandy beaches, coral reefs and more — and all in the same day if the timing is right!

The geology in brief

After being part of Gondwanaland in the southern hemisphere, the first sandstone deposits formed the Machinchang Formation during the Cambrian Period. The land was submerged during the late Cambrian, and the Setul Limestone Formation was deposited during the Ordovician Period. The Setul Formation continued to form during the Silurian Period, continuing into the mid-Devonian Period. The Chuping Limestone (not seen during this visit) was deposited by the end of the Permian Period. Sea levels rose, probably owing to a large tectonic event, which resulted in the emplacement of the granite beneath Langkawi at the end of the Triassic Period.

Age	Formation
Quaternary	
Triassic	Granite intrusion
Permian	Chuping Limestone
Devonian	Setul Limestone
Silurian	
Ordivician	
Cambrian	Machinchang Limestone

Our geo-trip was set for Friday 13 April 2007 — the Friday after Easter, and there were four in our party: my husband George, two friends from England and myself. Although we could have hired a car, we chose to hire a taxi for the day (six hours for less than £4.00 per person). The localities visited were: (1) Temurun Waterfall, (2) Pantai Pasir Tengkorak, (3) Pantai Pasir Hitam and (4) Sungai Kilim. Figure 1 shows their approximate locations.

Temurun Waterfall

The first stop was the Temurun Waterfall near Tanjung Buta on the north west of Pulau Langkawi. The 200m high, three-tiered

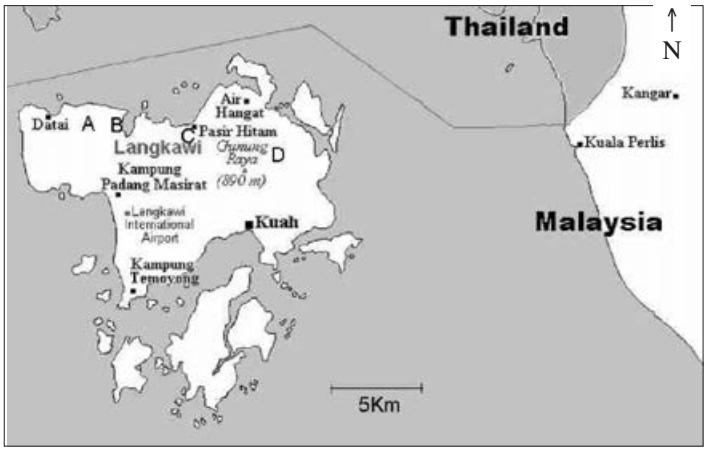

Figure 1 Map of Langkawi showing locations visited.

fall only has water for six months of the year and we were a little early for the rainy season. Thus we got a great view of the near-vertical cliffs of the late Cambrian Machinchang Formation in its drop instead. The waterfall exposes *c.* 150m sequence of this formation, being dominated by moderate to thickly bedded sandstone, with minor siltstone and shale beds. The sandstone beds show excellent internal planar crossbedding and were deposited in a shallow marine environment. The steep slope of the fall possibly represents a fault plane, but this is still ‘under investigation’. I had to take all this information as hearsay, as I had no intention of climbing up the steps to the side of the cliff in the late morning heat (and the abundance of mosquitoes didn’t help either — especially when I am usually taken to be their lunch!).

The water lying in Sungai Temurun was cool and crystal clear. Some local people believe the legend that the natural water pools possess healing powers, as there are numerous plant roots protruding into the pools.

Pantai Pasir Tengkorak

A short drive took us to Pantai Pasir Tengkorak (Sandy Skull Beach) at Tanjung Buta, where I could have stayed all day; but the others wanted to see more! The seawater here was clean, clear and blue, while the sand was so white that it dazzled. To the right-hand end of the beach are sandstones inter-layered with more resistant beds and large-scale erosion through the sediments.

The bedding is mainly layered horizontally, but some beds are tilted at different angles to each other. The gently dipping and warping sandstone and shale belonged to the upper part of the Machinchang Formation. The sandstone contains some excellent crossbedding. Here, the sandstone contains surface ripple marks, while the inter-bedded shale exhibits more interesting load-related sedimentary structures, such as load cast, flame structure, convoluted bedding, fluid escape features and truncated sandstone lenses (Figure 2, *opposite top*). The other unique feature is the salt desiccation-originated honeycomb-like structures called *tafoni*, particularly in the exposed shale. The strong relief of the *tafoni* reflects the maturity of the structure, while their shapes depend on the jointing patterns and the direction of the sea sprays (Figure 3, *opposite).*

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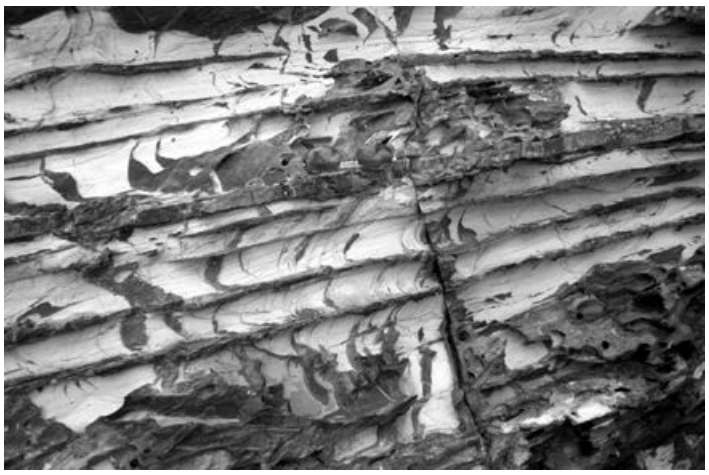

Figure 2 Weathering features at Pantai Pasir Tengkorak.

Figure 3 Honeycomb-like tafoni structures.

Pantai Pasir Hitam

Driving eastward past Lafarge Simen Factory (formerly Blue Circle), we arrived at Pantai Pasir Hitam (Black Sand Beach), so named because grains of tourmaline and limonite colour the sand black. And so you find us — four adults on a beach, looking at the cliffs fronting a raised beach and black sands, under umbrellas. Yes, Langkawi manages to maintain the EMi OUGS tradition of rain on a geo-trip on the Friday after Easter. Fortunately, it was a short, sharp shower — but we still got wet! We were looking at Quaternary sediments from the Holocene. The cliffs are being eroded and the black sand is made up mostly of sediment, a by-product of weathering and erosion of nearby granites. The processes have caused the rock to disintegrate to release its individual minerals, which are deposited on the beach. The sand consists approximately of 65% black minerals and 35% quartz. I noted that the black grains resembled a very fine powder, where the white/cream grains were 2–5mm in diameter, with some being round and others angular.

Pantai Pasir Hitam is a unique stretch of beach, as the sand on surrounding beaches is powdery and white (Figure 4). Langkawi is a land of many legends and so another local one states that the original sand was turned black by a mermaid who became angry with a fisherman for failing to keep a promise.

Sungai Kilim

Kilim is an area in the east of Langkawi — an area of karst scenery, with a mangrove ecosystem living on its limestone foundation. The dark grey, thinly bedded limestone of the Setul

Figure 4 Pantai Pasir Hitam (Black Sand Beach).

Figure 5 Setul Formation karst scenery at Kilim.

Formation is highly fossiliferous and the area features a landscape of nearly vertical to sub-rounded karstic hills and islands with pinnacles of various shapes and sizes separated by narrow valleys covered by the mangrove forests. Grey limestone walls hold hanging gardens. Kilim limestone contains numerous caves, tunnels, sea-notches, stacks and arches. This limestone, the Setul Formation, developed on a shallow ancient platform between the Ordovician and Devonian periods (490–370Ma), and is the second oldest rock formation in the Langkawi islands. We noted that there was a very apparent shelly bed, *c.* 0.75m of which was visible above the water line (Figure 5).

We opted to take a one-hour boat tour of Sungai Kilim, but in line with true Malaysian time keeping, this excursion took more than an hour and a half. The first stop was at Gua Kelawa (Bat Cave) which is home to Malaysian fruit bats. There are well thought out walk ways around and through the cave and we were easily (with torches) able to see the bats, stalagmites, stalactites and shell fossil beds, the last being remnants from when the sea level was 2–5m higher than present-day sea level.

The main chamber is a long tunnel where hundreds of bats cling to the ceiling. I was rather thankful for their clinging power, especially having many torches shone at them (Figure 6, *overleaf*)! There are stalactites at the eastern end of the cave, and they do not grow vertically downward — rather, the growth of these oblique structures is believed to be associated with deposition of travertine deposits by photosynthetic algae that required sunlight to grow.

The next stop on the river was a fish farm, where we had an interesting chat on some of the fish, their eating habits and teeth! Then an open-throttle journey took us to an apparent dead end. The boat stopped. Chicken skin was thrown over board. Then, as if waiting on a secret signal, the water was bombarded by birds of prey — striking chestnut-red Brahminy kites and white-bellied sea eagles. We were sitting in the middle of their feeding area. To see so many birds in flight so close was amazing — and for a short time eclipsed all thoughts I had about the geology (Figure 7)!

Tanjung Rhu

Another full-throttle journey quickly popped us out to the open sea, and then a brisk return to the jetty, from where we opted to drive to Tanjung Rhu for lunch.

Tanjung Rhu is a large, crescent shaped white sand beach, and it was so empty despite having two large resort hotels along its length. I remembered the beach from 15 years ago — one small resort and not a soul to be seen. Following a late lunch of *nasi ayam* (fried rice and chicken) we returned to our hotel to relax and review the day.

There is much more to see, geo-wise, on and around Langkawi and its islands, and more will be attempted on our next visit — hopefully in less than another 15 years! It will certainly include the cable car ride up to the peaks of the Machinchang Formation, where at 708m above sea level there is evidence of wave ripple marks; and a visit to Telaga Tujuh (Seven Wells) where the fairies were said to make shampoo from the limestone and plant roots — yes, you've got it — another local legend!

** UNESCO Geopark status was duly awarded in June 2007.*

More information on Langkawi and its Geopark can be found at www.langkawigeopark.com.my.

A few useful Malay words for geologists include:

Malay	*English*
buta	blind/without understanding
gua	cave
hitam	black
pantai	beach
pasir	sand
pulau	island
simen	cement
sungai	river
tanjung	headland
temurun	heritage

Reference

http://www.langkawigeopark.com.my/geopark_langkawi.htm (accessed 15 May 2007)

The author

Carol Hagan BSc Hons (Open), has been a member of OUGS since 1989, and after working in engineering for too many years now lives in Malaysia after having escaped the 'rat race'.

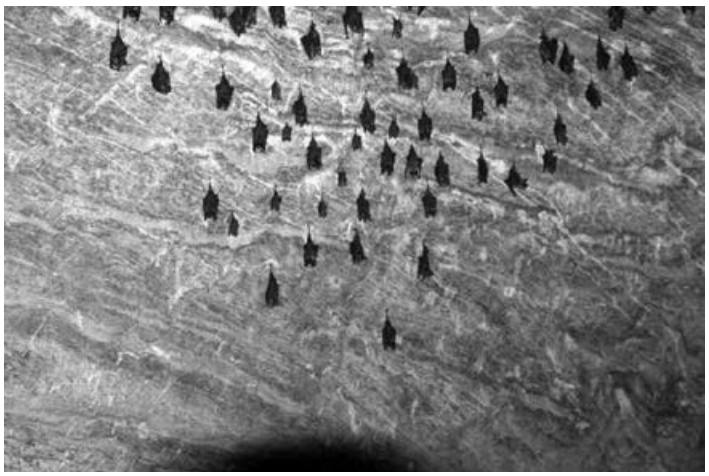

Figure 6 Bats in the cave at Gua Kelawa.

Figure 7 Brahminy Kites coming in to feed at Kilim.

Book review

John R. Nudds and Paul A. Selden 2008 *Fossil Ecosystems of North America*. Manson Publishing (ISBN 878 1 84076 088 0; paperback, 288pp; £24.95)

This book is a follow-up to their previous *Evolution of Fossil Ecosystems*, reviewed in *OUGS Journal* **27** (1), 22.

As the title implies, the authors have confined themselves to describing Lagerstätten on the North American continent. Inevitably there are some repeats of sites in the previous book: the Burgess Shale, Mazon Creek, the Morrison Formation and Rancho La Brea are direct reproductions of both text and illustrations. In addition to these well-known sites ten others are described, including the Green River Formation, the Gunfield Chert and the Hell Creek Formation, all of which are renowned worldwide.

As with the earlier volume, this book is easy to read, is packed with information and is beautifully illustrated. The history, geographical and geological position, and the flora and fauna of each site is described in detail.

These sites are important, and our knowledge of them contributes to our understanding of evolving ecosystems and increases our ability to define the processes that are relevant today.

— Jane Clarke MPhil (Open)

The Tongariro Crossing, Taupo Volcanic Zone, New Zealand: a steep geological journey

Colin Mould

Everyone has a perception of New Zealand before they get there, and for me (*Lord of the Rings* aside) it was volcanic, mountainous and earthquake-prone, with few people and a lot of sheep jokes. Setting to one side Bilbo, the people and sheep jokes, and starting with the North Island's geology around the area to the west of Auckland — where we stayed first — the big surprise was the degree of sedimentary structures, such as heavily folded and graded beds with well rounded conglomerate often seen in high-energy rivers. There was evidence of ancient volcanic activity around Piha's black sand beach, with an old volcanic plug and well eroded pyroclastic flows; however, that changed on arrival in the Rotorua-Maroa-Taupo-Tongariro Volcanic Zone.

The Taupo Zone

The Taupo (for short) Zone is the main 'modern' active geothermal and volcanic zone of North Island, and is the surface manifestation of the subduction of the Pacific plate under the Indian-Australian plate. The famous town of Rotorua, with its geysers and mud pools, is located in this zone. Surprisingly, in area it is very narrow: only some 20–40km wide, but more than 240km long. It is bordered by ignimbrite/pumice-covered, faulted and folded sedimentary greywackes (New Zealand Geological Survey 1972). Some of this zone is under the sea (Bay of Plenty) on the East Coast with the Hikurangi Trench and the active White Island volcano. This zone is under extension and moving apart at some 7–18mm a year. The last major eruption of the most active volcano (Ruapehu at the far end of the zone) was in was in 1995–6. The geographical setting of the zone is shown in Figure 1a and b.

The narrowness of this zone can be appreciated from Figure 2 — taken at Hell's Gate (Tikitere) just outside Rotorua — showing the mud pools, fumaroles and geysers of Hell's Gate and the rolling countryside outside of the fault lines, and giving an idea of the limited area of the zone. The main rock type here is low-iron ignimbrite/rhyolite/dacite. Many of the pools have high graphite concentrations and water temperature can exceed 115°C (Figure 3, *overleaf*).

The road from Rotorua to Lake Taupo is of great interest, with much to see, such as the Lady Knox geyser, the Wairakei steam field geothermal power station complex, the Hinekai Stream with its sinter flowers, the Tarawera Lake and associated volcano, and the Wai-o-tapu geothermal park … but that's a digression.

The Tongariro Crossing

The Tongariro Northern Crossing — a walk, theoretically horizontal, and of 17kms — goes across a complex of overlapping volcanic features, which includes some six craters, three cones, thermal springs, glacial reworking and associated lava and pyroclastic fields (Figure 4, *overleaf*, shows the profile and Figure 5, *overleaf*, the route).

This walk is a volcanologist's delight, but you have a limited time in which to do it, as the bus that drops you off collects you at the finish in eight hours; and it is a National Park, so no rock bashing is permitted. It is considered to be one of the best one-day walks in the world.

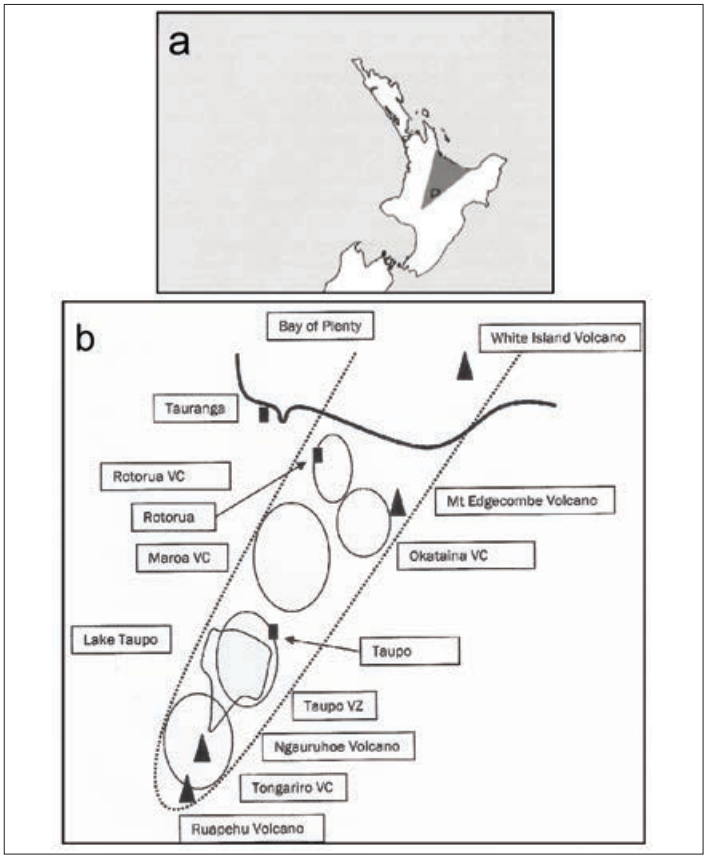

Figure 1 (a) Volcanic Zone, North Island; (b) Sketch of the Taupo Volcanic Zone and Volcanic Centres (not to Scale)

Please be aware it is *not* a guided walk. Although many hundreds of people may be walking it at any one time. you are on your own. Like all mountain walks the weather and conditions underfoot may change rapidly, so please note the warnings given in the Tongariro Park Map and be prepared.

The whole Taupo area is dated between 1.7Ma and the present, and is extruded through a series of lithologies. This includes a covering of andesitic tuff/ignimbrite, upper Quaternary marine sediments and laharic sediments, Pliocene sandstones and siltstones, upper and lower Miocene limestones, calcareous sandstones and siltstones, and, as the basement, Permian greywackes (New Zealand Geological Survey 1972).

Figure 2 General view: Hell's Gate and surrounding Taupo Zone.

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Figure 3 Graphite mud pool at Hell's Gate.

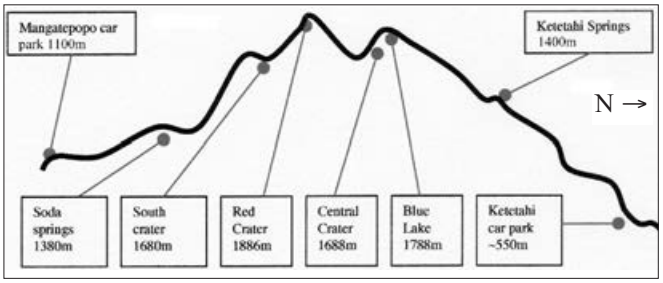

Figure 4 Profile showing features to be encountered along the Tongariro Northern Crossing (not to scale).

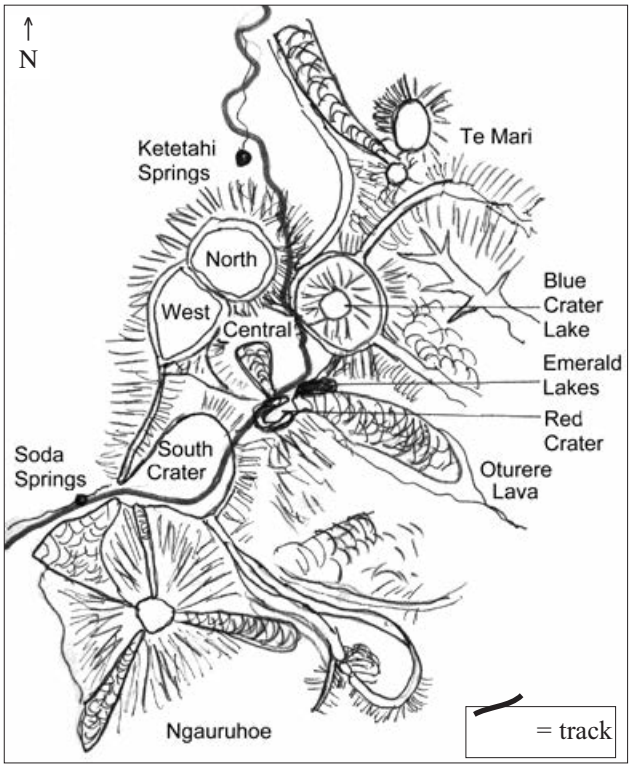

Figure 5 Sketch map of the Tongariro Northern Crossing route.

Lake Taupo was the scene of one of the biggest eruptions ever known, the Oruanui Eruption when it was estimated that more than 800km^3 of material blew out (*c.* 26,000 years ago) in what is considered to be *Phreatoplinian* (or super volcano) event (Wikipedia 2007). More recently, *c.* 230 AD, using tree ring data or 186 AD using Chinese and Roman records, some 60–100km^3 of material was erupted in an *Ultra-Plinian* event (Thornton 2003). Uniform ignimbrite deposits from these eruptions cover much of the area of the North Island — and can be seen in the desert road cuttings. As an idea of the size of the lake, the Waikato River that flows from it provides some 15% of New Zealand's hydro-electric power as well as cooling two geothermal power stations.

For non-walkers/geologists Lake Taupo is reputed to be the best trout and salmon fishing in the world; there is great jet boating on the outflow river; and you should see/eat the prawns from the local geothermal station's cooling water ponds! Best appreciated with a non-geothermal dry white.

This is still a very active volcanic region and Mount Ruapehu last erupted in 1995–6. In December 1953 a lahar from the Crater Lake on Mt Ruapehu washed out a railway bridge across the Tangiwai River just before the night express train arrived, resulting in the death of 151 people (Williams 2001).

The magma feeding the complex is derived from the descending Pacific plate from a depth of 75–150km. Andesite and basaltic andesite are the principal magmas of the Tongariro complex, but in the Taupo zone rhyolite and dacite are present. Much of the basaltic andesite is iron- and magnesium-rich (mafic) and oxidises into red scoria. Everything from ash (<2mm) to bombs (>64mm) and bigger can be seen or walked over.

You start the crossing at the car park (1,100m) and then a 'stroll' alongside/over the Mangatopopo Stream until you reach the Soda Springs (1380m). These are cold-water, high-gas-content mineral springs with iron oxide action from the surrounding bogs. Prehistoric and more recent (1870, 1949, 1954 and 1975) lava flows and pyroclastic deposits are seen on the flanks of Ngairuhoe and underfoot to the right as you walk around the flank of the volcano (Williams 2001) (Figure 6).

Then comes the real crunch test: climbing the outer rim of the South Crater, which exceeds 1:1 in some places. The climb is roughly 320m vertically and 700m horizontally (notionally about 1:2), but old lava flow blocks (*aa*) confront the hands and knees with slopes of over 60°. The lava blocks make climbing very difficult for those not built like mountain goats. If you make it without a coronary a treat awaits.

Figure 6 Mount Ngauruhoe (2,291m) and the South Crater.

From the top

Figure 7 *(opposite)* shows the climb of the South Crater western rim from the Mangatopopo Stream (at 1,380m). Old lava flows can be seen on the left. The Soda Springs are right-of-centre in the 'grass' section at the bottom of the slope in the photograph.

Figure 7 The climb of the South Crater western rim from the Mangatopopo Stream.

Figure 8 Inside the South Crater (a chance to regain one's.health).

Figure 9 View looking back from the rim of the Red Crater across the South Crater.

Figure 10 Lava tube in the Red Crater.

Figure 8 is inside the South Crater (1,680m) going towards the Eastern rim before a climb up to the Red Crater (top left). It is thought not to be a true crater but rather a glacial cirque even though tephra, prehistoric lava flows and explosion pits are present. These are often infilled with melt water and mud from Ngauruhoe in winter and spring. Blocks, bombs and lapilli can be seen from Ngauruhoe to the right. The local area of the Tongariro complex is about 275,000 years old, but the Ngauruhoe volcano is much younger at 2,500 years. It is made up of andesite/basaltic andesite pyroclastic ash and lava in a composite or strato-volcano (Williams 2001). There are occasional nuée ardente events, although the last eruption was in 1974–5. The eruption type then was 'Vulcanian' in that the vent was blocked by old lava and an explosive ash/pryoclastic eruption occurred when the magma chamber pressure was exceeded. It is estimated that the vent speed was about 400ms^{-1} or > mach 1 (Francis 1996). It is possible to walk to the top if very fit and you start the walk very early (this is a special trip/bus).

Figure 9 shows a view looking back from the rim of the Red Crater across the South Crater. The Western Crater rim is to the right; the 'pass' from the climb up from the Mangatopopo Stream is in the centre and the track can be seen to the left. Mudflows and melt-water patterns can be seen to the right.

One of the spectacular features of the trip is the Red Crater (1,886m). The red/russet colours are due to the iron in the mafic Basaltic and Andesitic scoria oxidising to the left of the opening (Figure 10). In the centre is a view of a partly open old lava tube (a dyke). This crater is still active and the last eruption was some 100 years ago. One eruption (*c.* 10,000 years ago) blew out the sidewall to the left and lava flowed down into the Oturere Valley. Another flow *c.* 230 AD went into the Central Crater (Williams 2001).

The highest point on the crossing (*c.* 1,888m) is the scoria rim of the Red Crater before the steep descent to the Emerald lakes (Figure 11). You can see volcanic steam issuing from the scoria, as the site is still active and the acidic Blue Crater Lake can seen in left background. This lake is an infilled splatter cone eruption between 25,000 and 10,000 years old and is acidic at pH ~5.0. If you are fit and a fast walker the lake can be visited as a deviation from the main track.

*Figure 11 The top of the Red Crater rim (*c*. 1,888m); volcanic steam rises from the scoria of this still-active volcano.*

The descent

Figure 12 shows the steep descent of the scoria slope to the Emerald Lakes. The range of debris sizes can be seen, although most of the descent is ash and gravel. However, at this point I was glad of any descent, as there had been a lot of ascent. The guide map advises running down it! Figure 13, a close up, gives an idea of the texture and steepness of the descent.

Figure 12 The descent from the Red Crater rim to the Emerald Lakes (centre of photograph).

Figure 13 Close up of the descent from the Red Crater rim.

Explosion pits on the breached rim of the Red Crater form the Emerald Lakes. These are not deep — *c.* 4.5m; but they are very acidic, with a pH of 3–5. Surprisingly, given the nearby fumarole activity they are cold, and their vivid green/blue colour is from polysulphide ions altering the leached mineralised melt water from the Red Crater. The track to the Blue Crater Lake goes off diagonally to the left and is, again, a bit of a detour from the main track.

Views of the *aa* flow into the Central Crater (*c.* 1,600m) is shown in Figures 14 and 15. This is *c.* 1800 years old and flowed from the Red Crater. The blocks are clearly seen, but the tenuous hold some plants have established does not come out well in Figure 14. Ngauruhoe is in the background to the southwest in Figure 14. The North and West crater walls are shown in the background with Figure 15.

Figure 14 a lava flow in the Central Crater.

A good reverse view of the Red Crater, the scoria slope — the Red Crater colours are not so vivid in greyscale — and the columnar jointing in the upper left corner can be seen in Figure 16 *(opposite)*. The darker colours are old lava flows and the range of debris is from ash to blocks. The Emerald Lakes are just off to the left. This is a good place to stop for lunch and have a breather, but however much you would like to take a foot-cooling paddle, it is *not* advised!

Figure 15 Figure 15. A dark aa *flow in the Central Crater flow from the left.*

At the bottom

Once down the slope a restful walk across Central Crater follows. Figure 17 *(opposite)* shows a reverse view of the complex including the scoria slope (highest point), the Red Crater (to the left) and the Central Crater's lava flow (flowing from the centre to the right). The active fumaroles can be seen steaming in the left centre. Ngauruhoe is in the background

Figure 18 *(opposite)* is a view of the start of the descent route down to the pick-up point near the lake. After a short climb over part of the North Crater rim from the Central Crater the track winds down the flank of the North Crater (on the left just discernable).

The boiling Ketetahi springs, mud pools and fumaroles are on sacred Maori land and no access is allowed, but the stream is often crossed and the steam from the springs can be seen. The descent

Figure 16 The Red Crater scoria slope.

to the Ketetahi overnight-refuge hut (ladies please note: these are the only toilets en-route) and on to the car park often crosses many old lava flows and is subject to small-scale landslides and erosion at any time, giving a bit of excitement and a need for careful walking when the path is erased.

Eventually, as you descend you enter the restored semi-tropical Ketetahi Forest (with podo-carp, beeches, *toatoa* trees and other species planted by the New Zealand Department of Conservation) and arrive at the car park after an exhilarating, but exhausting, eight-hour trek over a staggering volcanic landscape and looking forward to a cold, cold beer, a new set of feet and a hot bath … in that order. However, any thoughts of our triumph were soon diminished as Craig Morey, the owner of the Parklands Motor-Lodge — recommended as a base at Turangi — gleefully remarked when we limped/crawled/staggered in off the bus, "I told you to go fishing" — but he did open the bar!

Why no photographs of the nearly 2 hour descent? You must experience it yourself. I am not saying anything, but geology isn't high on the list!

References and further reading

If you do this trip it is well worth reading up a bit beforehand, to get maximum benefit; and there are many web sites with details about the geology of New Zealand and of this region.

There is a great deal of generalised information to be found on maps, pamphlets, notice boards and other such sources, at each site and at the various tourist or site offices. Unless otherwise stated I made most of these notes from such material and have supported them where possible from the references.

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Figure 17 Backview of the Complex and track.

Figure 18 View of the descent route, with Lake Raotoaria in the background.

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Further reading

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http://www.doc.govt.nz/Explore/002~Tracks-and-Walks/By-Region/007~Tongariro-Taupo/008~Tongariro-Crossing.asp [New Zealand Department of Conservation web site]

http://www.alpinescenictours.co.nz/alpinescenictoursTC.htm

http://www.wikipedia.org/wiki/oruanui [for further references and details about the Oruanui Eruption]

http://www.teara.govt.nz/earthseaandsky/

The author

After early retirement from a long career in the computer and electronic industries I became aware of the importance and complexities of geology during my Environmental Science undergraduate and post-graduate studies. Now hooked, I am taking an OU Earth Sciences degree (albeit slowly, and much to the annoyance of my wife!) in an effort to learn more about the geology around me as I travel.

OUGS Walton Hall Branch field trip to the Lizard Peninsula 18–21 May 2007, led by Professor John Mather and Dr Jenny Bennett

Tom Miller

Introduction

It is generally well known that the southernmost point of mainland England, the Lizard Peninsula of Cornwall, has some exotic rocks, including serpentines, gabbros, basalts, gneisses and schists. These are not commonly found elsewhere in the south of England. Of particular interest are the mafic and ultramafic igneous rocks (basalts, gabbros and peridotites) that make up most of the peninsula. In the extreme south and southeast there are strongly metamorphosed 'basal' rocks, at Lizard Point (gneisses) and along the coast up to Cadgwith (schists and gneisses), and again at Kennack Sands (gneisses) (Figure 1).

South of the front lies the ophiolite suite, wide areas of gabbro, peridotites ('primary' and 'recrystallised') and cumulates. The ophiolite sequence is much dismembered. At the extreme east (at Manacle Point) there is a basalt dyke swarm, trending south-east–northwest. In the far west (on Mullion Island), there are basalt pillow lavas. In the extreme south and southeast there are strongly metamorphosed sediments and volcanic rocks at Lizard Point and along the coast to Cadgwith and again at Kennack Sands.

Only the coastal sections are well exposed and readily accessible.

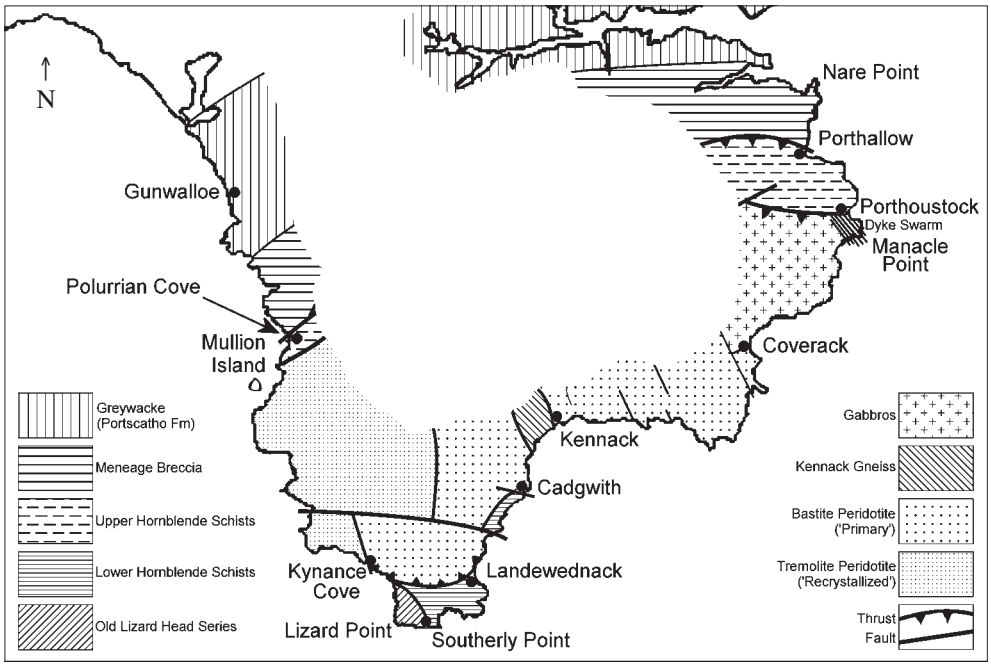

Figure 1 Simplified geological map of the Lizard Peninsula showing the locations referred to in the text (based on Colin M. Bristow 2004 Cornwall's Geology and Scenery, page 72, figure 45).

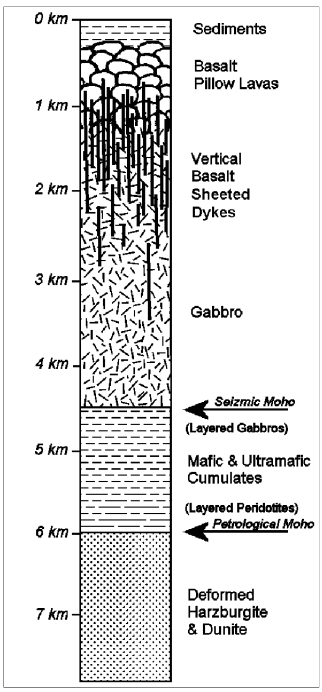

Figure 2 Idealised ophiolite sequence.

Geologists believe that the mafic and ultramafic rocks of the Lizard are parts of an ophiolite sequence. The distinctive structure and combination of rock types in an ophiolite sequence is shown in Figure 2.

An ophiolite sequence is the vertical succession of ultramafic and mafic rocks that make up oceanic lithosphere, from the mantle to the ocean floor. It is thought that ophiolites have occasionally been squeezed up (obducted) as thin slivers along the suture lines of continental collision belts, after ocean closure. They are generally seen as thin recumbent units, lying horizontally on adjacent continental lithosphere. It is thought that the Lizard ophiolite was obducted during Devonian times with closure of the Rheic Ocean, as the Armorican terrain collided with the Laurasian plate, ahead of the advancing Gondwanaland from the south.

The geological map (Figure 1) shows the main lithological units. The ophiolites are bounded in the north by a major thrust front that stretches from Porthallow westward to Polurrian Cove. The direction of the thrust was probably from the south or south-east. North of the thrust front lies a wide belt of breccia/mélange.

The trip

On Thursday evening, before the trip, our leaders Prof. John Mather and Dr Jenny Bennett described the tectonic history and regional lithology of the Lizard, and outlined the purpose of the trip. We were to spend the next four days investigating the ophiolite sequence and its relationships to the continental rocks around and beneath it. The itinerary was:

Friday

Locality 1: Porthoustock and Manacle Point, for West of England Quarry (gabbro quarry) and basalt dyke complex
Locality 2: Coverack, for ophiolite Moho boundary
Locality 3: Porthoustock (north), for hornblende schists
Locality 4: Porthallow (south), for boundary to Lizard Complex

Saturday

Locality 5: Mullion and Polurrian Cove, for junction of Lizard Complex and Devonian sediments
Locality 6: Kynance Cove, for the Lizard peridotites

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Locality 7: Gunwalloe Church at Church Cove, and Jangye Ryn, for Devonian sediments
Locality 8: Gunwalloe Cove fishing village, for raised beach

Sunday
Locality 9: Landewednack Church Cove and Quarry, for hornblende schists and junction
Locality 10: Southerly Point, for old Lizard Head series
Locality 11: Cadgwith, for rodingites
Locality 12: Kennack Sands, for the Kennack gneiss

Monday
Locality 13: Return to Porthallow, for the Lizard Boundary Fault and Meneage Breccia, and Nare Point

Friday localities

Locality 1: Porthoustock and Manacle Point

On Friday morning we set out for the West of England Quarry at Porthoustock. This location is at the northern limit of the gabbro sheet. An east–west fault line (thrust?) through Porthoustock separates the gabbro from hornblende schists to the north.

Owing to a Health and Safety Executive visit we did not go into the main quarry, but a short climb to the high ground behind the quarry showed its layout (Figure 3). There are three working benches producing graded aggregates, gabion stone and rock armour. The gabbro here is mostly orthopyroxenes (some clino-) with plagioclase. From here you can clearly see the flat 80m peneplain that extends widely around the West Country and Cornwall.

Figure 3 West of England Quarry, looking north.

We scrambled down to the coast at Manacle Point, where there is a dense basalt dyke swarm cutting up through the gabbro (Figure 4). The dyke swarm has a north to northwest strike and shows up to 80% density here, at sea level, becoming less dense farther south along the coast.

This is the only locality on the Lizard that has the sheeted dykes concordant with the ophiolite model, but their existence is undeniable. The basalt dykes show plagioclase phenocrysts, flow-orientated at the margins. No convincing 'chilled' margins were recorded. The gabbro between the dykes showed layering of plagioclase cumulates.

At beach level, Jenny Bennett pointed out an interesting exposure of young (Pleistocene) deposits, revealing a succession of cold climatic changes (Figure 5).

Figure 4 Sheeted dykes at Manacle Point.

At the base of the exposure, these deposits record a warm, interglacial period marked by large rounded beach pebbles at a time of raised sea levels. Above this, a distinct yellow horizon of loess (wind-blown glacial silt), indicates the really cold stage of the Devensian glaciation. Jenny explained that the loess may be 'datable' with good accuracy within the Pleistocene epoch (1.8Ma to 10ka BP) by a dating method called Optically Stimulated Luminescence (OSL). This uses the light re-emitted from irradiated minerals to measure the time interval of burial of sediments from the last time they were exposed to sunlight. The head deposits that overlie the loess contain angular clasts of gabbro and basalt and can show ice distortion features such as solifluction and ice wedges.

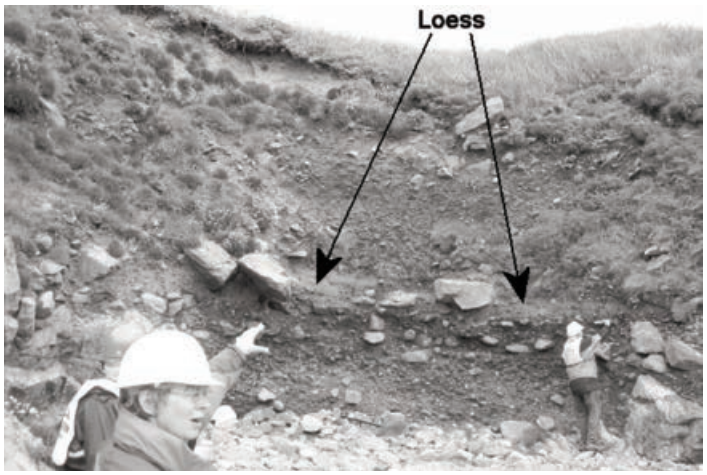

Figure 5 Pleistocene deposits at Manacle Point, showing a succession of cold climates changes.

Locality 2: Coverack

We stepped down onto the beach at Coverack, at the north end of the bay. This location is at the northern limit of the 'primary' bastite peridotite sheet. Here, the peridotites meet the gabbros in a transitional zone, supposedly in the mafic/ultramafic cumulates part of the ophiolite sequence.

On the north side of the bay there are large blocks of pale, layered gabbro with peridotite xenoliths (Figure 6, *overleaf*). The pale zones are rich in plagioclase. The peridotite xenoliths frequently show apple-green colour from veins of epidote within them.

Walking south, the rocks become darker in colour. Soon we were walking on 'inter-banded' gabbro and bastite peridotite (Figure 7, *overleaf*). The gabbro lies in thick sheets, inter-banded with the

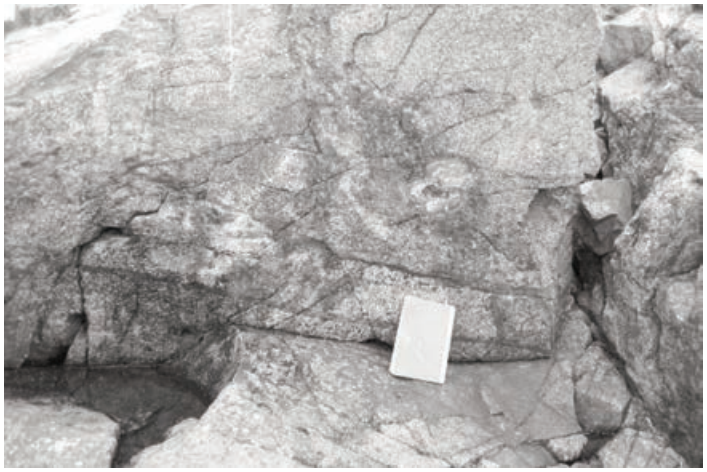

Figure 6 Peridotite xenolith rotting out of layered gabbro.

Figure 7 Inter-banded gabbro and bastite peridotite at Coverack.

peridotite. The bastite is a hydrated alteration of large orthopyroxine crystals in the peridotite, which gives them a distinct metallic lustre in the otherwise fine-grained ground mass. The bastite peridotite here is one of the least serpentinised peridotites on the Lizard. The interbanded gabbro and peridotite zone here must have coincided with the Moho discontinuity at the time of formation.

Continuing south, in the inter-banded gabbro/peridotite zone, there is a large pod of dunite, which is a peridotite that is highly depleted in pyroxenes and plagioclase. This is thought to be mantle peridotite after extraction of basaltic/gabbroic components. Ultimately, the gabbro stops and the rock becomes almost all bastite peridotite. However, closer to the harbour, there are bosses and veins of a speckled, lighter rock appearing more frequently in the peridotite. This is troctolite, a rare rock whose composition is transitional between peridotite and anorthosite (plagioclase) (Figure 8). The anorthosite crystals in its ground mass give it the lighter colour. It is thought to occur sometimes at the base of cumulate zones beneath spreading axes.

Locality 3: Porthoustock (north)

After ice creams at Coverack Harbour we returned to Porthoustock Cove, this time to look at the Upper Hornblende Schists north of the thrust fault line. We walked north from the cove, up a disused quarry track to some good exposures of the hornblende schists there. North of the fault line, the lithology is totally different from the gabbros to the south — there are no basalt dykes here.

The Upper Hornblende Schists are banded and dark in colour, but can have white banding and speckling. These are amphibolites, which are metamorphosed mafic igneous rocks of basaltic/gabbroic composition. Professor John Mather posed the question "What is their source?" Some discussion in the group raised the idea that the basaltic composition originated from source gabbros or basalts from the ophiolite complex, metamorphosed during emplacement of the ophiolite. John showed the chronology of the metamorphism to be early Devonian, while emplacement of the ophiolite did not occur until the late Devonian. We surmised that there must have been an earlier suite of volcanic rocks there, perhaps at significant depth, and it was these that were metamorphosed to become the Upper Hornblende Schists.

Locality 4: Porthallow (south)

We travelled to Porthallow to look at the region of the Lizard Boundary Fault shown as the major thrust front in Figure 1. This major boundary separates the hornblende schists from the Meneage Breccia crush zone to the north. The Meneage Breccia is believed to be the material that was piled up ahead of the advancing ophiolite unit at the time of emplacement.

A short walk along the beach southeast of Porthallow brought us to a curious assemblage of rocks (Figure 9). Along some 200m of beach we found peridotites, gabbros, basalts, mica schists, hornblende schists and a felsic gneiss. The rocks showed folding and shearing, suggestive of being close to a fault line. The assortment of rocks here is difficult to reconcile.

Figure 8 Rare troctolite, Coverack Bay (south).

Figure 9 Deformed rocks at Porthallow.

Proceeding north along the beach, we looked at the Lizard Boundary Fault at Porthallow. This fault, although not well defined, really looks more like a normal fault. Current thinking suggests that it was originally a thrust front, but later became reactivated by extension to give it its current form, downthrown to the south. There has been much movement and deformation to the rocks, evident some way from the fault line.

Saturday localities

Locality 5: Mullion and Polurrian Cove

On Saturday morning we set out for the west of the peninsula, to Mullion and Polurrian Cove. This location has affinities with Porthallow: it is on the east–west Lizard Boundary Fault; it has hornblende schists to the south; and it has the Meneage Breccia crush zone to the north (Figure 10). We looked at the rocks on the north side of Polurrian Cove first. There is a Devonian slate here (of the Portscatho Formation), much deformed.

Figure 10 John Mather discusses the Devonian Portscatho Formation at Polurrian Cove.

We walked south across the fault line. Looking eastward at the structure of the fault, it can be seen as a high-angle thrust from the south, but there has been some settling back. It is regarded as a 'normalised' reverse fault (Figure 11).

A Quaternary deposit was exposed near the fault. Jenny explained that there must have been periglacial conditions here — extended solifluction — to have moved so much of the head material in such a manner. Researchers have also applied pollen dating on these exposures, which has provided broad corroboration to the more precise OSL dating.

Figure 11 The Lizard Boundary Fault at Polurrian Cove.

South of the fault, there were the familiar hornblende schists, just as we had seen at Porthoustock (north). This was encouraging. This schist is seen as being the same tectonic unit — the Goonhilly Unit — as the Upper Hornblende Schists at Porthoustock. They are a metamorphosed basal unit on which the ophiolite rocks were obducted.

We walked south along the coast path towards Mullion Cove, from a high point above which we had a good view of Mullion Island. This inaccessible place is the only location where Lizard ophiolite lava pillows can be seen. We descended to the small harbour in the cove, where the sea wall and the protected quay are built of local stone. Granite blocks are used for paving and edging; serpentinites, schists and gneisses are used in the harbour wall (Figure 12).

Figure 12 The harbour wall at Mullion Cove.

Locality 6: Kynance Cove

Kynance Cove is in the far south of the peninsula where an east–west thrust fault marks the southern boundary of the Lizard peridotites. The thrust fault separates the ultramafic serpentines of the central peninsula from the schists and gneisses of the Old Lizard Head Series in the south. At Kynance, the fault, schists and gneisses are offshore but the serpentines can be studied closely at beach level.

Kynance Cove is a splendid place. The two main types of Lizard serpentine — bastite serpentine and tremolite serpentine — are both there in abundance. To the east is the bastite serpentine, which forms the high ground where the National Trust car park is. To the west is the tremolite serpentine, which forms a wide area up the southwest of the peninsula. The bastite serpentine is as described at Coverack, perhaps more serpentinised at Kynance, but with the same distinct metallic lustre in the large pyroxene crystals. The tremolite serpentine is much finer grained and banded. The tremolite serpentine is thought to be a reworked or 'secondary' serpentine (Figure 13, *overleaf*).

As well as the serpentines, there are basalt dykes at Kynance, felsic pods and banded gneiss visible at low tide.

Locality 7: Gunwalloe Church Cove and Jangye Ryn

We travelled north to Gunwalloe next, to look at a beach section of the Devonian Portscatho Formation. This is away from the ophiolite complex, but has interesting structural features that puzzled earlier geologists. First, however, we visited the small but splendid 15th-century church on the beach, only a few yards from the sea.

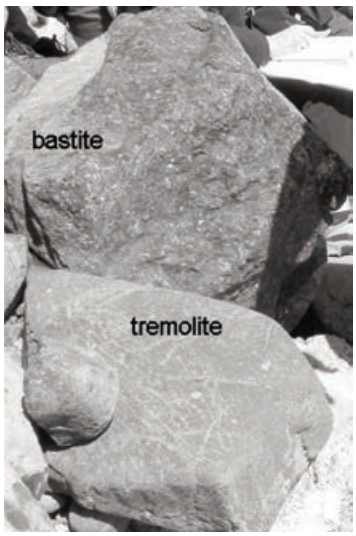

Figure 13 Contrasting samples of bastite and tremolite serpentine at Kynance Cove.

This church is under threat from the weather that hits the coast periodically. Heaps of boulders were placed on the windward side to give it protection. Walking northwest to Jangye Ryn, we came upon some large-scale chevron folding in the greywacke sandstone/shale sequence (Figure 14).

We spent some time here looking at deformation structures. This was part of the Carrick thrust deformation zone, north of the Lizard thrust. High up, structures showing overturn are clearly visible, as are quartz veins and tension gashes in the shales. Along the cliff tops there are freeze–thaw structures and evidence of gentle southward solifluction movement.

Figure 14 Large angular folding in greywackes, at Jangye Ryn.

Locality 8: Gunwalloe Cove fishing village

At Gunwalloe fishing village there are good remnants of a raised beach, suggesting a warmer climate (post Devensian) lying on dipping, cleaved Devonian rocks (Figure 15). There are big beach pebbles cemented in a finer matrix 'hard pan' in the remnant beach deposit, much like today's beach, and flints — perhaps from a chalk unit submerged out in Mounts Bay.

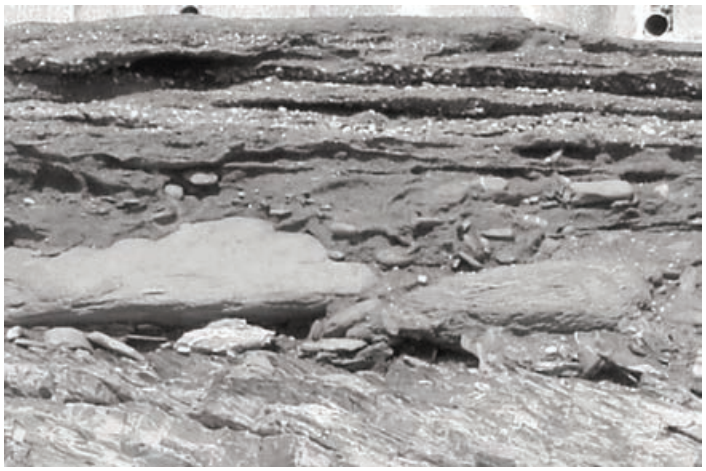

Figure 15 Raised beach deposit at Gunwalloe fishing village.

Sunday localities

Locality 9: Landewednack Church Cove and Quarry

On Sunday morning we set out for the far south of the peninsula, to Lizard village and nearby Church Cove at Landewednack. A nearby quarry exposes a thrust between two units of the Lizard Complex, separating the serpentinites of the central peninsula from the Lower Hornblende Schists to the south.

We walked from Lizard village eastward, down to tiny Church Cove. This is a narrow cove between high cliffs of the Lower Hornblende Schist. The schist here is differs from the Upper Hornblende Schists at Polurrian and Porthoustock in that it contains green epidote. Otherwise it has a similar basaltic chemistry. There are thick sills/lavas intruded in the schist here — an interesting clue to their origin. They contain zircon crystals dated at 500Ma. Possibly mafic volcanic rocks of Cambro-Ordovician age, metamorphosed to schists in the early Devonian.

A short walk northward from Church Cove (150m) took us to a small quarry above the coastal cliffs. Here, there is a good, clean contact between the Lower Hornblende Schist below, and bastite serpentinite above (Figure 16). This looks like a thrust surface with brecciation, dipping northwest at about 35°. If the peridotite was obducted from the southeast, why is it found on a surface that is dipping to northwest?

Figure 16 Serpentinite on Hornblende Schist at Landewednack.

One recent theory about the development of the Lizard Complex is that with the closure of the Rheic Ocean, the ophiolite was emplaced in a northwesterly direction, over a ridge of Ordovician rocks that are much metamorphosed and are now the hornblende schists. Ahead of the ophiolite thrust unit, a breccia/mélange pile built up that contained both mafic lavas and sediments (quartzites) torn from the ridge. This became the Meneague Breccia. The ophiolite and breccia slid down the northern slope of the ridge into the Gramscatho Basin during late Devonian times (this would reconcile the northwestward dip). At the climax of the Variscan Orogeny, compressive forces caused the Lizard Boundary thrust faults (north and south) to develop. Since then, the faults have 'normalised' enabling the ophiolite to settle between them. Erosion has exposed the slip plane of the ophiolite on the hornblende schist, at Landewednack.

At Landewednack, the serpentinite is cut by talc and asbestos veins. These are hydrated magnesian/ferro-magnesian silicate minerals from the serpentinite. Looking around the quarry, there are sheets of gneiss near the contact. John came across an example

of augen gneiss, which has eye-like segregations of pyroxene and feldspar components, due to the effects of shear stress at elevated temperatures (Figure 17).

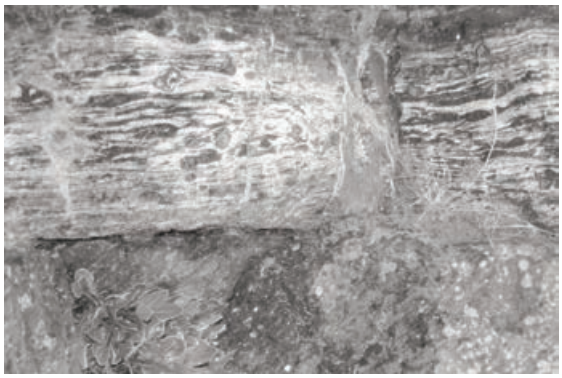

Figure 17 Augen gneiss, Landewednack Quarry.

The hornblende schists at Landewednack contain significant felsic, as well as the basaltic, components, all highly metamorphosed close to the peridotite junction. It is reported that there are gneisses and migmatites a little to the north (at Parn Voose) at sea level, containing mica. These would seem to be metasediments.

Locality 10: Southerly Point

We returned to Lizard village and walked down to Southerly Point, then down to Polpeor Cove. The boat ramp down to the cove has thick bands of mica schist on either side — folded mica schists and hornblende schists of Cambro-Ordovician age. It is possible to make out bedding. At sea level there are sheets of mafic rock (sills, lavas?).

These are rocks of the Old Lizard Head Series, dated at very nearly 500Ma (Figure 18). Perhaps these rocks formed a ridge over which the Lizard ophiolite was thrust during the Devonian period. They would seem to be the protolith that became metamorphosed to form the Lower and Upper Hornblende Schists. A thrust fault (unseen in the figure) separates the Old Lizard Head Series rocks from the Man-of-War Gneiss, on the small group of islands off shore.

Figure 18 Old Lizard Head Series rocks at Polpeor Cove.

Locality 11: Cadgwith

From Cadgwith fishing port, we scrambled up the coast path northeastward towards Kildown Point, where we looked at the rocks at Signal Staff Quarry. At this location, the thrust plane is not flat (as at Landewednack), but is complex, with sheets of mafic and pink felsic rocks (gneisses) inter-bedded in the peridotite (Figure 19). We walked some way down, off the coast path, to find a small (100–150mm wide) vein of rodingite in the peridotite (Figure 20).

Rodingites are calcium silicate veins of altered rock that occur in all serpentinites. They are white veins of garnet with minor amounts of serpentine, ilmenite and sphene. There are also dark, mafic dykes here and there, cutting through the gneisses and peridotite sheets. Both the rodingites and mafic dykes are the result of early hydrothermal action during the serpentinisation.

The gneisses are highly deformed and mylonitic near the base of the peridotite.

Locality 12: Kennack Sands

Finally, we travelled north to Kennack Sands to look at the Kennack Gneiss. This location is interesting because the major rocks of the Lizard ophiolite are present, but in a strange relationship. A mafic (gabbro) dyke cuts through the cliffs of bastite serpentinite (Figure 21, *overleaf*). A basalt dyke then cuts through both of these. The serpentinite mass and the mafic dykes are then all cut through (or intruded) by the Kennack Gneiss. The Kennack Gneiss is omnipresent and encloses the whole complex. This suggests an intrusion sequence of peridotite, gabbro, basalt and then gneiss.

Figure 19 Dark and pink gneiss sheets along the thrust plane near Cadgwith.

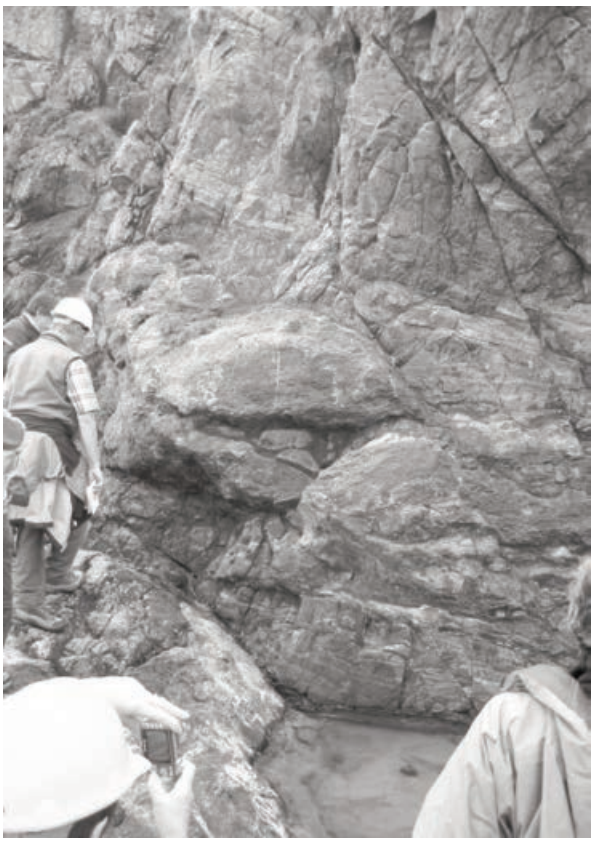

Figure 20 Rodingite vein near Cadgwith.

Figure 21 A Kennack Gneiss intrusion in bastite peridotite at Kennack Sands.

A possible explanation for the relationships is the different melting/flow temperatures of the rock types present. The cooling peridotite could, though solid, still be penetrated by flows of mafic magmas through faults in it. Then, on further cooling, the peridotite with the mafic dykes could, though solid, equally still be penetrated by the intrusion and flow of plastic Kennack Gneiss through joints and faults in its structure, particularly with the tectonic pressure of the thrust applied. Where the Kennack Gneiss penetrates the peridotite, there is alteration that has formed talc and asbestos.

Monday locality

Locality 13: Porthallow and Nare Point

On our last day we returned to Porthallow to walk the stretch of coast up to Nare Point. This location offers a good coastal exposure of the Meneage Breccia, north of the Lizard Boundary Fault. It was best appreciated as a final location, after all of the other locations had been studied.

On arrival at Porthallow, we re-visited a thin remnant of Devonian mica schist on the southeast side of Porthallow. Why was it there, south of the fault line? We made our way north up the coastal path from the cove. Up on the coastal path, John pointed out the famous location of Nelly's Cove, sketched by De la Beche in 1839, in which he recorded the form of the head deposit there. The head here is a permafrost-retained blanket, holding its stability angle of about 35°. The rocks of the Meneage Breccia are a brecciated mix of several sedimentary types, including slates, Ordovician quartzites, limestone and sandstone. It also contains a microgranite and pillow lava in Nelly's Cove. The coastline here has a distinctive morphology with multiple tongues or ridges of rock extending out into the sea, like groins (Figure 22).

At places along the section there are hard, white Ordovician quartzites at outcrop. The current view is that these quartzites had their origin as sand bodies in the Cambro-Ordovician Old Lizard Head Series to the south. It is thought that they were ripped from the ancient ridge crest during the ophiolite obduction and were metamorphosed in the process, finally coming to rest in the Meneage, north of the present day Lizard Boundary Fault (Figure 23).

One cannot help the feeling that this is too simple an explanation. There are artefacts such as the Devonian mica schist and other 'odd' rocks, south of the fault line at Porthallow. Why does the Meneage Breccia contain significant amounts of unmetamorphosed rocks from unknown locations? What is the context of the pillow lava in Nelly's Cove? What actually are the hornblende schists, in relation to the ophiolite? Predictably, our trip to the Lizard has shown us much, but left us with many new questions to answer.

Figure 22 The Meneage Breccia Coastline near Porthallow.

At Nare Point, we had reached the limit of our coastal walk. There are splendidly scoured surfaces in the Helford estuary that show the breccia/mélange textures very clearly. There are also nice exposures of the Pleistocene head with solifluction deposits, topped by loess. We spent a pleasant half-hour here, before the return walk to Porthallow.

Back at Porthallow, our trip came to an end. We had had an excellent few days on the Lizard with Jenny and John. It had been an extremely interesting and informative look at ophiolite processes, metamorphism, ancient thrust structures and Quaternary geology. We shall all return to the Lizard again, next time with a more informed perspective, and attempt to find answers to those new questions that we all have in our minds.

Figure 23 The Ordovician quartzite Meneage Breccia near Nare Point.

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The author

Tom Miller lives in Stevenage, Hertfordshire and enjoys natural sciences and the OUGS. He pursued a technical/engineering-based BSc (Open), completing in 1994, and since then has followed a career in technical publications. Tom is currently the Walton Hall Branch Organiser.

Trailback
Reading a mega-track-site somewhere in Jura

Rob Heslop

The Jura mountain range sprawls across the border of Switzerland and France. It forms a wide arc stretching for more than 250km, and developed *c.* 30 million years ago with the Alpine upward thrust. The Jura are the foothills of the Alps, and as if they were frozen shock waves, stand testament to geological upheaval.

The area harbours a multitude of flat-topped mountains, with high, vertical white cliffs packed with Jurassic strata (Figure 1). Indeed, it is from the white sedimentary stone within the Jura arc that the name 'Jurassic' derives.

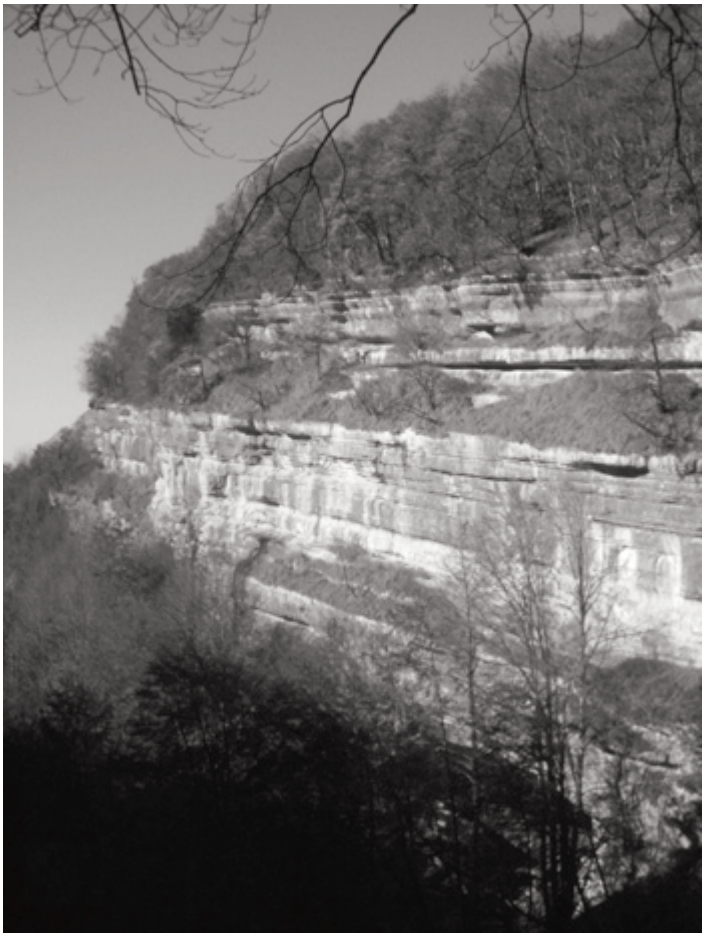

Figure 1 Typical Jura vertical cliffs toward upland plateau.

Fossils abound here. The majority of them are seashells, but other, rarer fossils also occasionally come to light. A few years ago for example, palaeontologist M. J. Mazin excavated an almost complete *Plateosaurus* dinosaur skeleton from a rock outcrop bordering the car park of a supermarket in the French town of Lons-le-Saunier. The animal dates from the end of the Triassic Period. Another large dinosaur fossil, a Stegosaurus, dating from the Jurassic, has been excavated from the Swiss side of Jura.[1]

Fossil trails have also been discovered, most of them in Switzerland, including a recent find at Courtedoux of sauropod and theropod dinosaur prints. To date, thousands of individual trace fossils have been cleaned from the Swiss sediments, which were deposited 152 million years ago. Tortoise shells and crocodile teeth were also revealed, petrified *in situ*, among the tracks; and in France, at an abandoned quarry near Loulle village, 50km north of Geneva, another mega-track-site has recently been investigated (Figure 2).

Site à pistes de dinosaures - Commune de Loulle
D'après les premières expertises ce gisement
est daté du Jurassique supérieur (- 155 millions d'années)
Les empreintes que vous pouvez observer ont été laissées
par des dinosaures sauropodes (dinosaures au long cou comme le Diplodocus)
Elles s'organisent en pistes et zones de piétinement.
Ces empreintes feront prochainement l'objet d'une étude par
l'Université Lyon 1 et le C.N.R.S.
CE SITE D'INTERET SCIENTIFIQUE EST UNIQUE,
TRES FRAGILE ET NON RENOUVELABLE.
TOUTE INTERVENTION :
FOUILLE, DEGAGEMENT, PRELEVEMENTS...
EST STRICTEMENT INTERDITE.
MERCI D'AIDER A LA PRESERVATION DE CE SITE PAR
LE RESPECT QUE VOUS LUI PORTEREZ.

Figure 2 A wooden display panel at Loulle Quarry.

First visit

I travelled to the area one dark autumn afternoon, booking-in to a *chambre de hôte* for the night. The next morning, after black coffee, croissants and friendly chat with the young lady of demure, I set off to visit the quarry. Freezing temperatures made winding roads hazardous, and combined with the morning's dense fog, finding the place was no easy matter in this, a rugged boulder-land 'Big Country' (Figure 3).

I eventually found the site, and shared my visit with only cold and silence.

Figure 3 Jura landscapes — after morning fog, the rocks and autumn woods are revealed.

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I trod among the ancient tracks, picking them out individually, and as the fog finally lifted, could clearly see fossil trails stretching right along to the foot of the quarry cliff edge. Some individual craters were almost a metre wide (Figures 4 and 5).

More than a thousand sauropod prints (both *pes* and *manus*) have been counted on this giant fossil floor. The vestige probably dates to the Jurassic Oxfordian Stage of *c.* 155Ma, when the area was a lagoon and sandbank, bordering warm shallow seas. Sauropods came here successively over many years and their prints show throughout several thick, overlaying horizons within the quarry (Figure 6). Would this infer that the large herbivores had remained in this specific area throughout all of that time; or were they trailing back on a migratory route, time and again, over decades, and perhaps even many tens of centuries?

Throughout last summer, the site was investigated by a scientific group from Lyon University, and a further two years of research is estimated for this remarkable context, before final scientific conclusions are published.

Figure 4 A sauropod print on a giant fossil floor (the beer bottle provides an indication of scale).

Figure 5 Scientists marked for examination individual trails leading to the quarry edge (the central, darker line of footprints has been painted red on the site, and appearing darker down the centre in the figure).

Figure 6 Prints scatter the foreground, with many other prints of overlaying steps in the background.

Early research

The limestone series of the Jura range was initially described by A. von Humboldt in 1784. Later in 1829, famous geologist Alexandre Brongniart labelled the Jura limestone 'Jurassic', which subsequently became an entire geological timescale. Various natural history enthusiasts contributed to a growing collection of Jura fossils, including in 1862, the first regional dinosaur discoveries.

Some of these early collections are held in several local museums. Other specimens travelled the globe. For example, the French palaeontologist J. Marcou took his large Jura collection to Cambridge, Massachusetts, USA, while working there as a geology teacher.

It was only relatively recently that dinosaur fossil trails from the region were first recognised.

Probably the earliest research concerning fossil prints and tracks commenced in America with E. B. Hitchcock beginning in 1835. He investigated the Connecticut Valley area, and extracted large patches of fossil-bearing rock, which he stored in the Appleton Cabinet college museum, eventually causing the entire ground floor of the building to become overwhelmed with the collection.

Hitchcock correctly identified the red sandstone fossils from the valley as belonging to the late Triassic; but incorrectly suggested that his ever-growing mega-track specimens were traces of a diverse and now extinct group of birds. He was never to learn that the many hundreds of classifications that he listed were in fact fossil trails from three-toed (thus bird-like), primitive thecodont dinosaurs. In 1865 he even excavated what appeared to be lizard-type fossil prints, but remained steadfast that these too had been left by large unknown birds (Figure 7, *opposite*).

A few years before his lizard-type fossil footprint find, dinosaur *Hadrosaur* fossils were being scrutinised in America by J. Leidy, a pro-Darwinian. Elsewhere, G. Mantell and R. Owen were describing the *Iguanodon* from England, and D. Buckland the *Megalosaurus*; and the great Cope-Marsh dinosaur bone rush was about to begin.

Effectively at this time, a new, wider understanding of life's grand diversity was about to unfold, but it was also during this time that Hitchcock died, thus before the true dinosaurian identity of his life's collection was realised.

Figure 7 The Loulle Quarry cliffs. How many more prints remain to be discovered in these strata?

It is owing to the work of these pioneers of palaeontology, zoology and geology, and of others, that the descriptive system of academic conclusions and listing bibliographic documents commenced; and it is through the accumulation of on-going constructive earth science papers and bibliographies that a wider appreciation of the natural world spread; and indeed ever since, the continual stream of short academic pieces have helped fill, in part, the puzzle of the 'Big Picture'.

From those early days of big dinosaur discoveries, revolutionary evolutionary ideas, and Cuvier's comparative anatomies, as well as the growing collection and cataloguing of fossils, including trace fossil mega-track-sites, that stimulating and even overheated academic debates, ensued.

From these developments a whole field of trace fossil studies has grown, and now has a life of its own, called 'palichnology' (or sometimes paleoichnology).

Dinosaur track

Fossil dinosaur tracks have biological names that describe the morphology of the print, and are thus not the name of the animal that might have left them. For example, The ichnogenus *Brontopodus* trail describes a wide-gauged quadruped track of sauropod genus, whereas *Anomoepus* and *Grallator* are bipedal dinosaur trails (initially Hitchcock's 'birds'). *Eubrontes giganteus* represents a large carnosaur track-type group, and so on.

In the American state of Massachusetts, dinosaur tracks are so widespread that they are classified as the official State Fossil. New fossil trails frequently come to light from around the globe.

On the Isle of Skye in western Scotland, *Grallator* dinosaur prints and tracks have been investigated, dating to the Bathonian of the mid-Jurassic Period; and on the coast of the English Channel, a complex overlay of fossilised tracks has also been excavated recently from within both Purbeckian and Portlandian limestone beds, dating to near the end of the Jurassic Period. Even ancient conifer woods and other fossilised foliage have been recovered from this remarkable site. The whole sequence provides almost enough detail to illustrate the entire ancient ecosystem of that area.

Wanting to see these remains, I had a brief opportunity to do so while working as an archaeological guide in Northumberland in the summer of 2007, but was unable to do so for lack of time and due to the distances involved — the Scottish dinosaur mega-track-site was 300km to the north, and the English track-site was more than 400km south. It was only upon my return to France and to my every-day-job as a teacher, that I first learned of the recent French-Jura-discovery (Figure 8).

Figure 8 Another fragment of the ancient shallow seabed found in Loulle Quarry.

Research at Loulle and Coisia

The head scientist of the Loulle investigation is M. J. Mazin, the man who had previously recovered the Jura *Plateosaurus*. He has written several academic papers, and has thus contributed to that long list of earth science publications. I sifted through a sprawling Lyon library, and eventually found some of his works.

In one of them — 'La Locomotion des Ptérosaurs' — he describes an incredible 'quadruped' Pterodactyl fossil trail (which reminds one of an on-land scuttle from a flying reptile), dating to the Tithonian Stage of 140Ma at Crayssac in south-western France. The Tithonian (also known as the Portlandian), is thus similar in age to the English Channel site described above. More than 40 other trails have also been identified from this fossil area, including crocodile prints.

While searching information concerning the fossil trails at Loulle, I read of yet another track-site in the French Jura range, near the small village of Coisia in the Haute Jura National Park.

The Coisia prints and trails (Figure 9, *overleaf*) had been found and thoroughly investigated a year before to the Loulle discovery, and a report concerning the site had been recently published. With only one brief phone call to the Parisian academic establishment of 'Palevol' I was sent a copy of the academic report, which arrived within a few days bearing the big-black-stamp 'Institut de France'.

A road project had cut through a Jurassic limestone stratum beyond the Coisia village and revealed a large flat slice of rock of Tithonian Jurassic period (*c.* 141Ma). This is the final Jurassic stratigraphic unit, bordering the beginning of the Cretaceous period (often referred to locally as the Chailley Formation) (Figure 10, *overleaf*).

Figure 9 The entire rock face at Coisia is strewn with trails.

Figure 10 More prints from the Coisia site.

Figure 11 A fresh slice at Coisia, containing more trails.

After a few months, when the new, wider road near Coisia was opened, the 'fresh' dinosaur trails were noticed, and later examined by palaeontologists led by Jean Le Loeuff (Figure 11). They later discovered more sections farther along the road, which had been slightly eroded.

There are altogether 200 visible prints. Detailed measurements and study showed them to belong to a sauropod (thus perhaps similar to the Loulle site), and they were identified with the ichnogenre name of *Parabrontopodus* (a narrow-gauge sauropod track-site); the trails had probably been left by an *Apatosaurus* (Brontosaur) type animal, or perhaps by a European *Diplodocus*.

Anatomical calculations concerning the locomotion of these fantastic animals (perhaps up to 30m or more in length) has been done by A. McNeil of Leeds University. Using the Froude Formula, whereby the stride length reveals the leg height, and even the animal's locomotion speed, McNeil has concluded that *Apatosaurs* were very slow moving indeed. They may have been able to trot 'elephant style' at *c.* 7km per hour. In contrast, McNeil concludes that the *Diplodocus* species may not have even been able to trot, owing to their much lighter, more fragile skeletal frame.

Most dinosaur mega-tracks illustrate a walking-paced locomotion, as indeed do the fossil trails at Coisia. The animals here were advancing (almost) at a Human walking pace. McNeil reminds us that this is slow for an animal with legs stretching up to 3m in height!

The sequence at Coisia, which appears in several segments, shows at least nine individual trails, inferring that these large herbivores travelled in small groups across the wet Tithonian/Portlandian flats (Figure 12).

There are also fossil burrow trails[2] scattered along the rock face, indicating the presence of tube-dwelling shrimps (*Thalassinid*), and together with ammonites, gastropods and bivalve fossil shells, demonstrate that this area was also within a shallow, tropical tidal flat zone — again similar to the Loulle site.

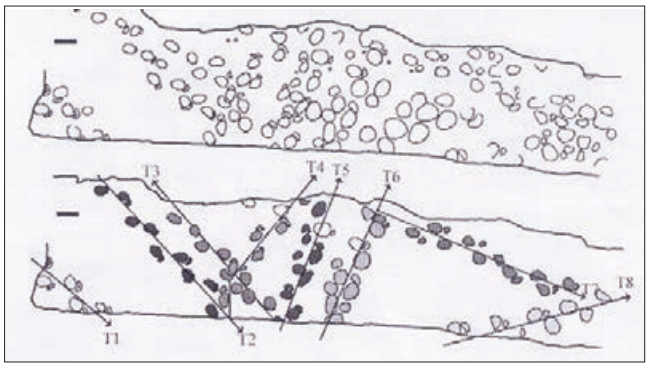

Figure 12 An interpretation of trails: (1) all prints, with metre-bar scale; (2) a simplified interpretation is that T4, T5 and T6 seem to have walked as a group (sketch J Le Loeuff et al.*).*

Visiting Coisia

I found time one windy morning to travel to Coisia with my young fossil-frenzied son Matty (aged 4), to see this massive fossil floor.

After millions of years the entire context has been twisted and turned vertically (through the geological process of the Alpine upheaval). It is indeed astonishing to see this shoreline relic, twinned with the vivid prints, now in an almost upright position, 500m *above* today's sea level.

This long fossil slab stretches a few hundred metres and remains parallel with the uphill road. Without doubt there are more remains in the overlying rock, as well as under the road. Indeed, the team of searchers who studied the site in 2005 hint that potentially there are several thousand square metres of continuous 'unseen dinoturbated' fossil floor, preserving yet more fossil footprints.

Figure 13 Matty next to a sauropod print.

Figure 14 Back at Loulle Quarry — as if washed onshore, an empty beer bottle rests upon fossil ripple marks.

This smaller mega-track-site, compared to the Loulle vestige, was more evocative to me, for I could understand it. After reading the conclusions reached in the Palevol report, I could now actually 'read' the fossil floor. I showed Matty where two sauropods had walked in cumbersome elephant-style, side by side, and from which direction they had come. Another animal had followed parallel, farther along. Later, yet others, probably of the same species, plodded along the segment from yet another direction, occasionally stepping among the first set of prints.

Within the wet sands, crustaceans had burrowed, perhaps waiting for a return of the warm waters of the ancient Tithonian tides (Figure 13). This entire kaleidoscope was 'baked' by the warm tropical airs, before being covered in fine silts, probably brought along by incoming waters, and thus preserved (Figure 14).

At the present rate of discovery, surely more tracks and trails from within this mountainous, fossil-rich region will come to light, giving yet further insight into the strange 'Age of the Dinosaurs'.

Notes

[1] In 1995, fossil dinosaur prints were found strewn along a busy farmyard in France's Dordogne region. They were later identified as belonging to a primitive Stegosaur and fitted neatly to a theoretical Stegosaur-trail-type illustration, recorded by Australian paleontologist T. Thulborn, several years before this, the first Stegosaur-trail discovery.

[2] Fossilised burrows and tunnels are known as 'domichnia', and concern the study of palaeobiology.

Acknowledgement

The author would like to thank Jean Le Loeuff for his kindness, information and e-mails.

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The author

Rob Heslop lives in France in a village south of Lyon, with his wife and three children. He works as an English teacher and is currently studying prehistoric archaeology long distance with Exeter University. He also takes OU courses. He writes numerous short articles on prehistoric archaeology *(see also pp 19–23 in this issue),* and palaeontological topics, and joins in excavations.

Book Review

A. C. Ries, R. W. H. Butler and R. H. Graham (eds) 2007 *Deformation of the Continental Crust: The Legacy of Mike Coward*. London: Geological Society Special Publications **272** (ISBN 978 1 86239 215 1; hardback, 595pp; £100)

Mike Coward (1945–2003) was an influential structural geologist whose ideas, enthusiasm and passion for geology prompted his friends and associates to produce this collection of papers that outline and expand on the areas of his interest throughout his career. During his relatively short life he worked on projects in many parts of the world, including north-west Scotland, Africa, the Himalayas, North and South America, China and the North Sea, where he developed new ideas and applied them to structures across geological time, location and scale.

The 29 papers in this anthology echo the course of his career and encapsulate and develop his research themes. The topics covered include:

- Deformation processes in the deep crust in the Lewisian of north-west Scotland
- Shear, both pure and simple, as seen at crustal scale and in local structures
- Fold patterns of the Moine Thrust belt and the relationship between minor structures and major thrust surfaces
- Simple shear and stretching in carbonates of the Southern Apennines of Italy
- Extensional tectonics and coeval exhumation of buried crust in the north-western Himalayas and in the Oman Mountains, with further models derived from extensional processes in the Cyclades
- Regional scale studies of orogenesis in Central Africa Irumide Belt, the Taurus Mountains, the Colombian Cordillera and the subduction of the Nazca Plate in South America
- Review of salt mobility and basin evolution in offshore Brazil
- A user's guide to seismic interpretation to deduce salt structures in the North Sea
- A report on small-scale laboratory experiments to model basin structures and their reactivation in transpressional settings

Applications of theory led to papers on:

- A worldwide review of hydrocarbon prospectivity in foreland fold and thrust belts
- The implications of the timing on hydrocarbon systems with reference to Colombia
- The numerical modelling of the effect of fracture swarms on fluid flow in chalk following field studies in south-east England
- The geometry and evolution of structures controlling fluid flow in hydrothermal systems with respect to gold mineralisation

The book is well produced, with a variety of maps, diagrams and some colour illustrations. Unfortunately in places the diagrams and maps are reduced in size and difficult to read. I struggled with the complexity and technical detail of some of the papers, and with 595 pages there was a great deal of information, all well referenced. My knowledge is limited, as I have yet to study continental rocks (S339), but it has wetted my appetite for exploring hard rocks and their structures. This volume would serve as a reference in this field and appears to be a just legacy to the work of Mike Coward.

— Averil Leaver Cert Ed and OU Earth Sciences student

Book and map review

D. T. Aldiss, A. J. Newell, N. J. P. Smith and M.A. Woods 2006 *Geology of the Newbury District: A brief explanation of the geological map sheet 267 Newbury* and map *England and Wales sheet 267 Newbury bedrock and superficial deposits*. Keyworth, Nottingham: British Geological Survey (ISBNs not given; paperback, 34pp (including separate map); £18)

This publication comprises two parts: the map and an accompanying 34-page booklet. The area covered may be most familiar to many as the chalk downland, visible on both sides of the western section of the M4 between Reading and Swindon, taking in Chieveley and Membury services. Cretaceous chalk, uplifted in the late Palaeogene when the London Basin formed, dominates almost all the area covered, with the exception of Newbury and Greenham Common in the south east, dominated by Quaternary gravel deposits mostly laid down by the River Kennet system.

The map — BGS 1:50,000 sheet 267, showing bedrock and superficial deposits (terms replacing the older 'solid' and 'drift') — is a considerable improvement on the older series maps, with additional cross sections and a computer-derived 3D model of the chalk. It is also printed more conveniently, so that the whole map can be viewed without unfolding the whole sheet.

The accompanying booklet, subtitled 'a brief explanation' of the map, provides considerable added value. It is intended "both for those who may have limited geological experience and for the professional". For the latter, there are full references, details of the sources used and additional resources available from the BGS, including references to digital geological maps available for use within a GIS. This review, though, is from the former perspective (limited geological experience).

Following the introduction, providing a good overview of the geological processes affecting the area, the main section is a detailed geological description of the area, period by period, effectively explaining the processes that formed the landscape we see today. The focus (covering between them over half of the section) is on the Cretaceous and the Quaternary, during which almost all the visible geology of the area was formed, and the text is augmented with photographs and diagrams, including detailed stratigraphies and borehole logs.

The final short section of the book, 'Applied geology', covers topics such as water resources and geohazards. It provides only a cursory, high-level introduction, but it does touch on the features of the chalk aquifer, commercial mineral extraction, foundation hazards and flooding. The detail would not be sufficient to inform activities such as building or excavation works, but the final 'Information sources' and references sections provide pointers for further study.

Overall, the book and map together provide an easy-to-use resource essential for anyone wishing to study the geology of the area in depth.

— Gillian Sheldrick BSc Hons (Open)

Editor's notes

Dear OUGS Members,

First of all, please accept my apologies for the late publication of this issue of the *OUGS Journal*. Its tardiness is due to computer problems, which now appear to be sorted.

Thank you for your patience.

Following are guidelines for the submission of articles to the *OUGS Journal*. The principal theme encompassed within these guidelines is 'please keep it simple'. Let your editor do his job and please do not try to simulate, emulate or reproduce the page layout of the *Journal*. I have dedicated page-layout software (QuarkXPress) to do this and any special formatting, special characters and embedded illustrations that you include in a word-processing document can be lost (at best) or seriously confuse and crash (at worst) my iMac or the QuarkXPress software when I import it into the layout.

If your article contains special characters (such as mathematical symbols), please draw these to my attention (I will probably spot them anyway) so that I can import them properly with the glyphs menu in QuarkXPress.

Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

Guidelines for *OUGS Journal* articles

As *OUGS Journa*l Editor I do not want the publication of your paper to be more work than is necessary for you (or for me!). Your paper need not be more than about 1,500 to 4,000 words in general, but I leave the length up to you to suit the material.

Regarding papers from the presenters of lectures at the OUGS Symposium, all OUGS members are grateful to you for presenting a talk at the OUGS Annual Symposium, and for agreeing to submit a version of your talk for publication in the *Journal*. The purpose of this is to make your information available to OUGS members and others who could not attend the symposium. As OU students and OUGS members we enjoy hearing and learning the information these symposia bring.

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2007 Winner, Category A Geologically inspired landscape: Katherine Addison-Scott "Concretion balls a.k.a. 'Field of Marbles'"

This amazing sight is in the Parque Nacional Ischigualasto, Argentina. They call it the 'Field of Marbles', presumably for giants. They are actually spherical concretion balls of hard rock that had formed in soft sediments millennia ago, during the Triassic Period. The area was a vast floodplain dominated by rivers, with extremely seasonal rainfall and received a lot of volcanic ash. As the softer support matrix eroded these balls were left stranded. As further erosion takes place more balls are exposed and the number of 'marbles' increases. Unfortunately for me, but fortunately for the site, people are not allowed into the area so I could not see the concretions close up.

2007 Commended, Category A: Jenny Forrest "Black Tor — Dartmoor"

A small tor, one of many on Dartmoor, but an example of the result of 280 million years of erosion, uplift and weathering of the Dartmoor granite.

2007 Commended, Category A: Linda McArdell "Colourful Cretaceous, Lux, Portugal"

These colourful sediments are of lower Cretaceous age: Aptian limestones overlying undifferentiated marls — accumulations of terrigenous and marine material on the sea floor in a shallowing environment as the Tethys Ocean closed. The outcrop of dark rock at the far end of the beach is volcanic material of late Cretaceous age (Alpine Orogeny), from a sea floor volcano, piercing the accumulating sediments, and now exposed as the cliffs erode. They are easily accessible on the beach at Luz, Portugal.

2007 Winner, Category B Geological feature or structure: Linda McArdell "Aa-Aa — Pahoehoe"

This photograph was taken in either 1999 or 2001 at the bottom of Chain of Craters road on Big Island, Hawaii. Much of the lava on this western edge of the East Rift Zone came from Mauna Ulu between 1969 and 1974 and has caused the road to be remade on a number of occasions. The small dribble of slate grey pahoehoe *lava on top of the brown rubbly aa-aa was so perfect that when revisiting the site in 2001, I had to look to see if it was still there, and photograph it again. See maps for recent lava flows. http://hvo.wr.usgs.gov/kilauea/update/maps.html. Chain of Craters road is the black squiggle to the bottom left of the overview map.*

2007 Commended, Category B: Jenny Forrest "Basalt Rose"

*A stone rose "Rosa de Piedra" on the island of Tenerife , formed in a basaltic flow that has been constrained in some way during its flow and cooling, perhaps in a lava tube or by flowing down the course of a "*barranco*" or valley. The cooling, taking place perpendicular to the flow, has created the radial pattern.*

2007 Commended, Category B: Jenny Forrest "Serpentine — Coverack Cove, Cornwall"

A close up photograph of a bastite- serpentinite boulder on Coverack beach, Cornwall . In this example the calcite stockwork " lightning" gives a very regular and pleasing pattern.

2007 Winner, Category C Industrial geology: Linda McArdell "Parys Mountain Copper Mine, Anglesey

Parys Mountain on Anglesey is a text-book example of a copper deposit generated from oceanic circulation at a mid-ocean ridge with black smokers and the characteristic stockwork. The copper mine is now known to have been worked intermittently since 3500BP (early Bronze Age). It was last worked ~1880, and is now just a series of spoil heaps with >100 sealed-up shaft entrances. The colour in the spoil is from metallic residues and the photograph of it is enhanced by patches of purple heather and a brilliant blue sky. (Red/yellow Fe3+ hydrous oxides, diverse sulphate minerals with Cu, Al, Fe, K, Pb and Zn. Intense weathering is due to the highly acidic environment from the oxidation of pyrites.)

2007 Commended, Category C: Don Cameron "Sand Pile, East Leake, 2004"

Mineral processing, the sand and gravel is washed and classified and this heap was forming interesting 'landforms' caused by the sand sticking together, and the water eroding the various lumps — micro-geomorphology in action!

2007 Winner, Category D Popular vote: Tony James "Interference Patterns — rock pool — White Scar Caves, near Ingleton"

This photograph was taken in the White Scar Caves near Ingleton, one of the Field Trips offered at the Lancaster University Symposium 2007. It is of a rock pool made from flowstone (usual stuff). The effect, I think, was caused by a combination of low, ambient light in the cave (so very little blurring of the image); lots of dripping water from the cave roof (it had been raining previously); and very still air in the cave, giving perfect intersecting ripple circles on the water's surface. The photograph was taken on a Kodak Easyshare DX7630 digital camera, not even an SLR! I must confess that I was quite surprised when I looked at the result from such a simple camera. I was only expecting a photograph of flowstone and rock pools, but the interference patterns were quite startling.

2008 Winner, Category A Geologically inspired landscape: Dave Talbot "Mammoth Hot Springs of Yellowstone Park, Montana"

These terraces have formed and indeed, are still forming above the Yellowstone Caldera in Wyoming, USA. As hot groundwater cools on exposure to the atmosphere, dissolved calcium from limestone rocks through which it has passed is deposited to form travertine. Where this process is ongoing micro organisms flourish and give the travertine various colours — green, yellow, orange, etc. When the plumbing is blocked — for example by a small earthquake, or the tubes are otherwise closed-off, the travertine takes on a white, then grey discolouration. In the end it disintegrates to clay-like components. These terraces cover a large area and are a huge draw for many thousands of tourists and scientists who visit Yellowstone each year.

2008 Commended, Category A: Dave Talbot "Grand Canyon of the Colorado River from Desert View, on the south rim, Arizona"

This view of the canyon includes almost all of the rock formations that form the canyon. The Tonto Platform forms the flat expanses at the base of the photograph — these are Cambrian in age. Below them, in the incised gorge of the inner canyon, the Precambrian rocks are metamorphosed schist, intruded by granite, and faulted. The change between these is known as the Great Unconformity, which lasted more than a billion years. All formations above the unconformity are sedimentary rocks: sandstones, limestones and shales, almost all flat-lying; the top, Kaibab Formation is only of Permian age. All rocks are Palaeozoic, and the Cambrian and Permian rocks are Devonian and Carboniferous; there are no known rocks of Ordovician or Silurian age.

2008 Winner, Category B Geological feature or structure: Jenny Forrest "Pillow Lavas at Boatman's Harbour — New Zealand"
(Jenny Forrest's photograph of the Boatman's Harbour pillow lavas was also Runner-up in Category D Popular vote.)
Classic pillow lavas from the Oamaru volcano on the east coast of New Zealand's South Island. The Oamaru eruption was an intra-plate eruption that took place 40Ma ago into shallow seas. The pillows show glassy rinds and radial cooling joints and fractures. Between the pillows there is a pale limestone formed from the lime mud of the sea bed.

2008 Winner, Category C Industrial geology: Dave Talbot "Bingham Copper Mine Terraces"

This the mine is c. *25 miles from Salt Lake City, Utah, USA, is more than 2.5 miles wide and 0.5 miles deep. Excavations in the area known as Bingham Canyon started in 1863, initially for gold, mainly placer deposits, then for lead and silver when the gold started to run out. Although copper had been found some years earlier it was not until 1896 that mining for it was started; open-cast operations were initiated in 1906. As the pit enlarged over the years many small towns and settlements were abandoned and destroyed, the last being the town of Lark. Of the communities that made Bingham Canyon as diverse as it was only the town of Copperton remains.*

Today winning the ore is a highly mechanised operation, and along with the copper many other metals are recovered, including gold, silver and molybdenum. About one-third of the rock is ore and two-thirds is waste.

2008 Commended, Category C Industrial geology: Linda McArdell "Body of Rock, Palma, Majorca"

*This statue is in the garden of the Museum / Cathedral complex in the centre of Palma, Majorca. The rock looks like travertine (limestone precipitated in a hot spring environment) [*cf *"Mammoth Hot Springs of Yellowstone Park, Montana" on preceding page-spread — Ed.], but without defacing a work of art in a public place it would be difficult to find out what it is actually made of. The banding and golden colour is particularly attractive.*

2008 Winner, Category D Popular vote: Dave Talbot "Cliff Collapse, Ashdown/Wadhurst Formations, Pett Level, East Sussex"

No two visits to Pett Level or Cliff End, whatever you like to call it, in East Sussex are the same; cliff falls occur frequently. I passed by an initial fall earlier in the day, heading toward Fairlight Cove, but returned later hoping to see more. Mainly sand- and siltstone deposited in the Wealden environment of the Lower Cretaceous, there is also an important industrial ironstone at the junction between the Ashdown and the Wadhurst Formations here.

The cliffs are highly jointed, between 25–30m high, with a normal fault to the east and a reverse fault to the west — hence the many falls. The falls expose many trace fossils — dinosaur footprints, ripple beds, burrows, and even occasionally dinosaur bones, small crustaceans and tracks in fallen blocks.

I waited about 30 minutes, taking several other photographs while doing so, before the collapse occurred. I had positioned myself at an angle to the cliff in a position I believed would be safe. This photograph shows the cliff face looking like a waterfall, but instead of water, it is formed by a rain of fine sand particles. The fall lasted only a few seconds and was pervaded by an earthy smell in the air around me.